Volume 33 OCTOBER, 1949 Number 10

BULLETIN
of the
American Association *of* Petroleum Geologists

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BULLETIN

of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

OFFICE OF PUBLICATION, CHESTNUT-SMITH BUILDING, TULSA, OKLAHOMA

THE BULLETIN is published by the Association on the 15th of each month.

EDITORIAL AND PUBLICATION OFFICE AND ASSOCIATION HEADQUARTERS, Chestnut-Smith Building, 624 South Cheyenne Avenue, Tulsa, Oklahoma. Post Office, Box 979, Tulsa 1. Cable address: AAPEGOL.

SUBSCRIPTION PRICE to non-members is $15 per year (separate numbers, $1.50), prepaid to addresses in the United States; outside the United States, $15.40.

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	Mem.	*Non-Mem.*
Cloth-bound Bulletin, Vols. 13 (1929)-15 (1931) incl., each	$5.00	$6.00

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Entered as second-class matter at the Post Office at Tulsa, Oklahoma, and at the Post Office at Menasha, Wisconsin, under the Act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized March 9, 1913.

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, INC.

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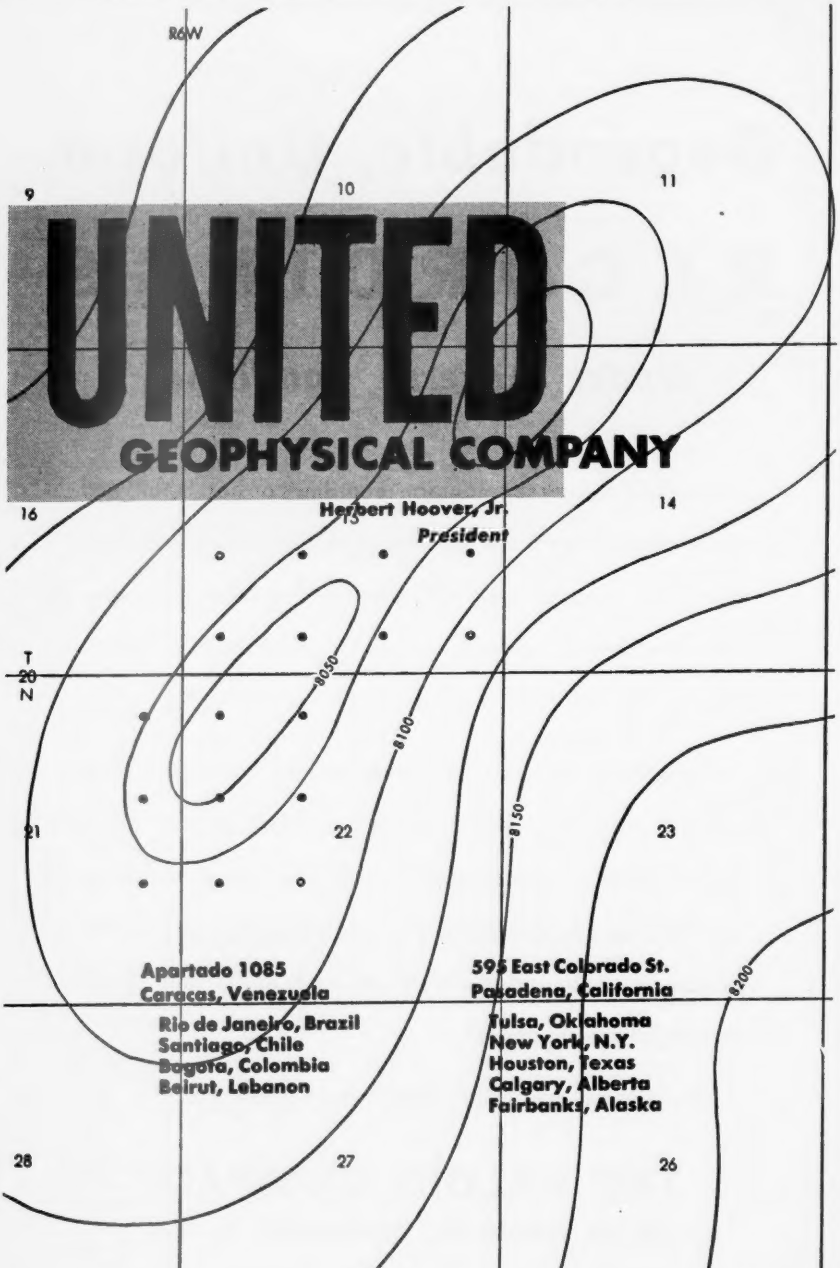
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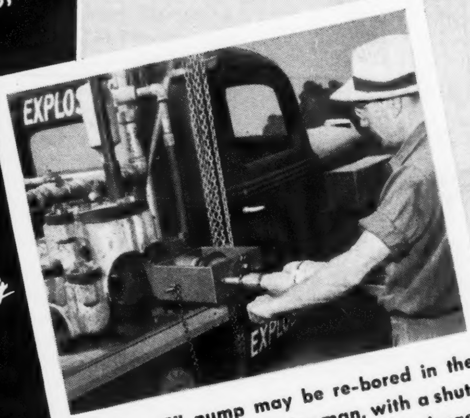

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Report No. 5

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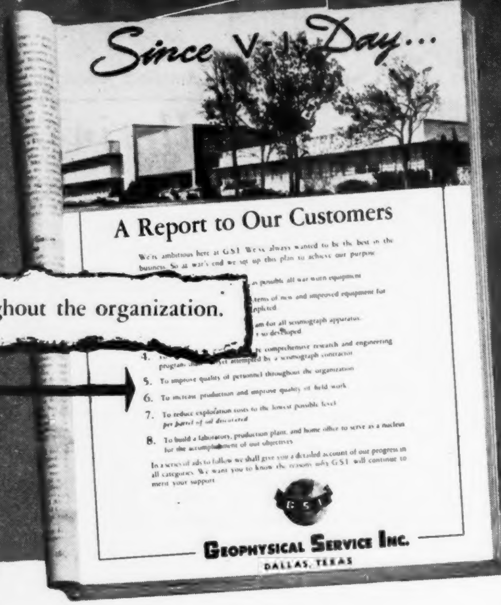

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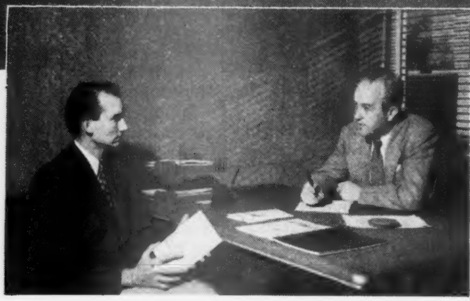

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BULLETIN
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OCTOBER, 1949

EVOLUTION OF THOUGHT ON STRUCTURE OF MIDDLE AND SOUTHERN APPALACHIANS[1]

JOHN RODGERS[2]
New Haven, Connecticut

ABSTRACT

The first men to comprehend the structure of the Appalachian Mountains were the brothers Henry D. and William B. Rogers, who from 1835 to 1842 studied the mountains from northern New Jersey to southwest Virginia. They worked out the Paleozoic stratigraphy of the area and by means of it deciphered the folds of the middle Appalachians and the thrust faults of the southern Appalachians. They attempted to explain the structure as the result of great explosions on the southeast; beginning with Dana, however, later geologists have generally ascribed it to lateral compression.

Since the time of the Rogers brothers, many structural ideas have emerged from the study of the Appalachians, such as the geosyncline, underthrusting, erosion thrusts, and the competence of strata. Prominent among the many investigators was the group of geologists headed by Willis and Hayes, who late in the nineteenth century worked out several of the low-angle, large-displacement thrust faults of the southern Appalachians and attempted to explain the mechanics of Appalachian structure.

In recent years two schools of thought have been developing with regard to the depth of Appalachian deformation. One school holds that all large folds and faults extend down to, and are supported by, the basement; the other holds that the deformed rocks have been stripped completely off the basement along one or more great bedding-plane thrust faults.

INTRODUCTION

The Appalachian Mountains, which extend along the eastern side of North America from Newfoundland to Alabama, are classic ground for structural geology, for here many of the major concepts of the science were developed. Moreover, Appalachian structure is still a subject of fascinating interest and of much controversy, and we may confidently expect that many additional discoveries

[1] Published by permission of the director of the United States Geological Survey. Read before the Association at Pittsburgh, October 5, 1948. Manuscript received, March 11, 1949.

[2] Department of geology, Yale University. The writer wishes to thank Chester R. Longwell of Yale University, Richard E. Sherrill of the University of Pittsburgh, Berlen C. Moneymaker of the Tennessee Valley Authority, and Philip B. King, Robert A. Laurence, and Charles B. Hunt of the United States Geological Survey for critical reading of the manuscript. King took an active interest in the preparation of the paper, and his comments have been especially valuable. Those who took part in the discussion at Pittsburgh when the paper was presented have also contributed to the paper. Francis X. Bland drew the figure.

will be made and many new and fruitful ideas will be formulated here in the future. It is therefore fitting to pause in our labors and controversies and to review the evolution of thought that has created our present concepts.

Ignoring Newfoundland, we may describe the Appalachian chain as a series of three sweeping curves, each convex on the northwest (Fig. 1). These curves extend in turn from the Gulf of Saint Lawrence to New York, from New York to Roanoke, and from Roanoke southwestward. The corresponding segments of the

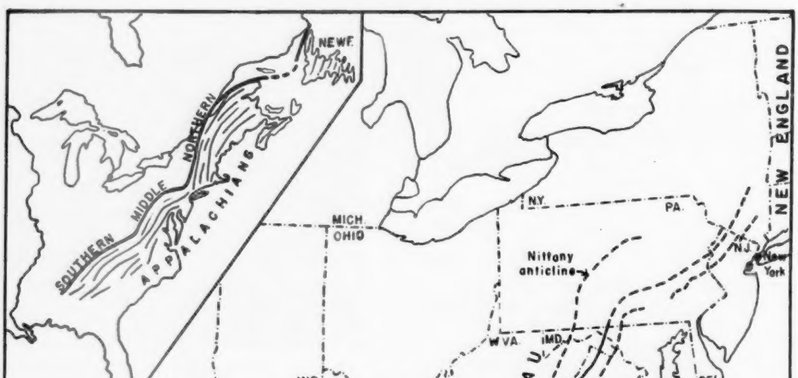

FIG. 1.—Principal structural features of Valley and Ridge province in middle and southern Appalachians.

chain, which differ considerably in structure, may be designated respectively the northern, middle, and southern Appalachians. The northern Appalachian segment was affected by at least three major orogenic episodes during the Paleozoic; it is therefore more complex than the other segments, and much of its geology is still obscure. The chief structural features of the middle and southern Appalachians, however, at least of the unmetamorphosed parts, appear to have been formed in a single period of deformation. The following discussion refers almost exclusively to these two segments.

Southwest of New York, the Appalachian region may also be divided longitudinally into three unlike belts. On the northwest is the Appalachian Plateau, where the rocks lie nearly flat excepting along a few outlying folds such as the Sequatchie anticline in Tennessee and Alabama. In the center is the Appalachian Valley and Ridge Province, where the rocks are markedly folded and faulted but remain almost entirely unmetamorphosed. On the southeast are the Blue Ridge and the Piedmont Plateau, where the rocks are characteristically strongly metamorphosed. These belts grade into each other in some places, but in many parts of the middle and southern Appalachians their boundaries are surprisingly sharp. This paper deals chiefly with ideas about the structure of the central belt, but some mention of the other belts is made where necessary.

PIONEERS

The deciphering of Appalachian structure began in the years 1835 and 1836, but it is profitable to turn back even farther and examine the ideas that were current before it was realized that there was any Appalachian structure. The first determined attempt at a synthesis of the geology of eastern North America was that of William Maclure[3] (1763–1840), who published a geologic map of the United States in 1809. In 1809, the use of fossils to determine the relative age of rocks had just been discovered in England and France and was apparently unknown in America. Maclure therefore classified rocks on the system of Abraham Gottlob Werner, according to whom the relative ages of rocks are to be determined from their lithologic character and their attitude. On this system, the crystalline rocks of New England and the Piedmont were classed as Primitive, the tilted and disturbed rocks of the Valley and Ridge Province as Transition, the flat-lying consolidated rocks of the Appalachian Plateau and the Mississippi Basin as Flötz or Secondary, and the unconsolidated sediments of the Coastal Plain as Alluvial. Thus, rocks now known to be Paleozoic were distributed among three of the four grand divisions. The steep dips of the Appalachian rocks were considered primary and in fact the distinctive mark of the Transition class. Appalachian structure presents no problem to one who believes that the rocks were originally laid down in their present attitude!

[3] William Maclure, "Observations on the Geology of the United States, Explanatory of a Geological Map," *Trans. Amer. Philos. Soc.*, Vol. 6 (1809), pp. 411–28, map. Same, revised and enlarged, *Trans. Amer. Philos. Soc.*, New Ser., Vol. 1 (1818), pp. 1–91; also separately published at Philadelphia (1817).

Approximately 20 years after Maclure published his map, the ideas of William Smith on dating rocks by their fossil content, which were revolutionizing European geology, became current in America, and, about 1835, they led to a great outburst of geologic activity. By joint study among the flat-lying rocks of New York state, Ebenezer Emmons (1799–1863), Lardner Vanuxem (1792–1848), and James Hall (1811–1898) established once and for all the standard Paleozoic section for North America. At the same time, the serious study of the Appalachians was begun by the two Rogers brothers: Henry Darwin Rogers (1808–1866) in New Jersey and Pennsylvania, and William Barton Rogers (1804–1882) in Virginia, which then included West Virginia. Though employed by different states, the brothers worked closely together; shortly they succeeded in establishing a stratigraphic column for the folded Appalachians and in unravelling the structure. In 1835 inklings of the true explanation of the tilted and disturbed strata of the area came to the brothers; during the summer of 1836 H. D. Rogers and his assistants in Pennsylvania found the stratigraphic key, and the nature, amplitude, and extent of the great Appalachian folds became apparent. During the next year or two, W. B. Rogers and his assistants worked out several of the thrust faults of southwest Virginia and showed their relations to the folds.

In 1842 the two brothers presented a summary of their findings to a meeting of the Association of American Geologists and Naturalists, the organization that later became the American Association for the Advancement of Science, in an address[4] which is a milestone in American geology. In the first part of this address the phenomena are described with a clarity that is enviable to-day. Particularly emphasized are the marked asymmetry of the Appalachian folds and the common occurrence of overturned dips, the general northwestward decrease in the degree of asymmetry and overturning, the great length and remarkable parallelism of fold axes and fault traces throughout the chain, the constant relation of thrust faults to anticlinal axes, and the contrast between the predominantly folded middle Appalachians northeast of Roanoke and the predominantly faulted southern Appalachians farther southwest.[5] Ever since the publication of this paper, the middle and southern Appalachians have been recognized as the typical folded mountain range.

In the second part of the address, the brothers attempted to explain the phenomena so well described; this part of the address is as curious and quaint as the other is straightforward and modern. On the one hand, they rejected the ver-

[4] W. B. Rogers and H. D. Rogers, "On the Physical Structure of the Appalachian Chain, as Exemplifying the Laws Which Have Regulated the Elevation of Great Mountain Chains Generally," *Assoc. Amer. Geologists and Naturalists Repts.* (1843), pp. 474–531. Reprinted in W. B. Rogers, "A Reprint of Annual Reports and Other Papers on the Geology of the Virginias," New York (1884), pp. 601–42. See also the brothers' annual reports to the State legislatures of Pennsylvania and Virginia, 1836–1842, and the final reports by H. D. Rogers on New Jersey (1840) and Pennsylvania (1858).

[5] Only a little later (*Assoc. Amer. Geologists and Naturalists, Proc. 6th Ann. Meeting* (1845), pp. 49–50), the brothers announced the additional discovery that slaty cleavage in the Appalachians and elsewhere normally lies parallel with the axial planes of folds.

tical forces previously in vogue to explain all disturbed strata as unable to account for the observed asymmetry of the folds; on the other, they rejected tangential pressure working alone as unable to explain the extraordinary parallelism. Instead they proposed to combine vertical and tangential forces, setting both in operation by a great catastrophe. They pictured the sedimentary crust as thin and flexible, lying on an indefinite thickness of fluid lava that contained gases under high pressure. Shortly after the deposition of the Coal Measures, the gases escaped in a series of sudden explosions from fractures just southeast of the present folded belt. Each explosion set up waves at the surface of the lava, causing undulations of the overlying crust to travel northwestward as in a rug shaken at one end. The explosions also produced great tangential forces which gave the waves in the lava and the undulations in the crust their pronounced asymmetry. Finally, as the lava congealed at the site of the explosions and near-by, forming the igneous rock bodies of the Blue Ridge and Piedmont, the undulations were frozen into place as the folds we now see.

This bizarre theory was apparently not accepted by the Rogers' contemporaries, but for many years geologists argued the relative merits of vertical and horizontal forces as causes of the observed deformation. Gradually the tangential theory, advocated especially by James Dwight Dana[6] (1813–1895) and impressed on the minds of generations of students through his textbooks, gained supremacy. To-day probably no geologist doubts that the folds and faults of the Appalachians are the result of lateral compression. Similarly Dana's view that the deformation took place in a single episode that marked the end of the Paleozoic has become traditional.

Somewhat later, another important generalization was drawn from the facts of Appalachian geology. In 1857, in a presidential address before the American Association for the Advancement of Science, James Hall[7] pointed out that in the Appalachian Mountains the Paleozoic sediments of the eastern United States reach their maximum thickness, and he suggested that such a relation between mountains and thick shallow-water sediments was a general rule. To Hall, the sediments were especially thick in the Appalachian region because they were localized there by a great ocean current from the northeast, and because the crust sagged under their weight, making room for more. He sought to explain the mountains solely as the result of uplift and erosion of the thick sedimentary sequence, for he believed that the folding and faulting of the Appalachian rocks was a minor effect of the subsidence of the sediments during their deposition and had nothing to do with the presence of the mountain chain. As had happened with

[6] James D. Dana, "On the Origin of Continents," *Amer. Jour. Sci.*, 2d Ser., Vol. 3 (1847), pp. 94–100.

———, "Geological Results of the Earth's Contraction in Consequence of Cooling," *ibid.*, pp. 176–88.

[7] James Hall, "Contributions to the Geological History of the North American Continent," *Proc. Amer. Assoc. Adv. Sci.*, Vol. 31 (1883), pp. 31–69. See also *Natural History of New York, Part VI, Paleontology*, Vol. 3 (1859), pp. 1–96.

the Rogers brothers 15 years earlier, Hall's induction from the facts was soon recognized as valid, but his explanation for it was not accepted. In 1873 Dana,[8] proposing the term geosynclinal for the trough of thick sediments, suggested that tangential forces best explain both the trough and the subsequent orogeny. The further vicissitudes of the idea of the geosyncline do not relate to our topic, but it is noteworthy that the idea began in the Appalachians and that the Appalachian geosyncline is the type geosyncline.

Following the Rogers brothers, many geologists carried on the study of Appalachian structure. Outstanding was the work of James Merrill Safford[9] (1822–1907) in east Tennessee, where the thrust faults of the southern Appalachians reach their greatest development. He was apparently the first to describe the Sequatchie anticline and the Pine Mountain fault, which lie somewhat northwest of the main belt of Appalachian folding and faulting. Safford was an early champion of the theory that the folds and faults were caused by tangential forces from the southeast. Later the structure of northern Alabama was studied by Eugene Allen Smith[10] (1841–1927) and his associates, one of whom, Alexander M. Gibson,[11] discovered the faulted anticline of Murphrees Valley, which in contrast to practically all other Appalachian folds is overturned toward the southeast. As they accepted the view that the Appalachians were deformed by tangential forces acting from the southeast, Smith and Gibson[12] introduced the concept of underthrusting to account for this fold.

In the middle Appalachians, the Second Geological Survey of Pennsylvania under Peter Lesley (1819–1903) restudied the folds of Pennsylvania and delineated them on fairly detailed geologic maps. Lesley and John James Stevenson (1841–1924) also studied the thrust faults of southwest Virginia.[13] Stevenson believed that these thrust faults were considerably later than the folding, perhaps of the same age as the faults cutting the Triassic rocks of New England and the Piedmont. Both Lesley and Stevenson, like their predecessors, thought of the

[8] James D. Dana, "On Some Results of the Earth's Contraction from Cooling, including a Discussion of the Origin of Mountains, and the Nature of the Earth's Interior," *Amer. Jour. Sci.*, 3d Ser., Vol. 5 (1873), pp. 423–43; Vol. 6, pp. 6–14, 104–15, 161–72.

[9] James M. Safford, *Geology of Tennessee.* Nashville (1869). Much of this material had appeared in Safford's first biennial report in 1856.

[10] See *Reports of Progress* of the Alabama Geological Survey, beginning in 1873.

[11] Alexander M. Gibson, "Report on the Geological Structure of Murphrees Valley," *Alabama Geol. Survey Spec. Rept. 4.* Montgomery (1893). Gibson made his discovery in the late eighties.

[12] Alexander M. Gibson, *op. cit.*
Eugene A. Smith, "Underthrust Folds and Faults," *Amer. Jour. Sci.*, 3d Ser., Vol. 45 (1893), pp. 305–06.

[13] J. Peter Lesley, "On the Coal Formation of Southern Virginia," *Proc. Amer. Philos. Soc.*, Vol. 9 (1862), pp. 30–33.
J. J. Stevenson, "The Faults of Southwest Virginia," *Amer. Jour. Sci.*, 3d Ser., Vol. 33 (1887), pp. 262–70.
Details in papers by Lesley in *Proc. Amer. Philos. Soc.*, Vol. 12, and by Stevenson in Vols. 19, 22, and 24.

Appalachian faults as high-angle breaks on which the movement was largely vertical upthrust.

WORK OF UNITED STATES GEOLOGICAL SURVEY

In 1887, the United States Geological Survey, formed only 8 years earlier, sent a group of young men into the southern Appalachians. Bailey Willis, the oldest of the group (he was barely 30), was in general charge of the investigation; under him Marius R. Campbell (1858–1940) worked chiefly in southwest Virginia, C. Willard Hayes (1859–1916) in northern Georgia and Alabama, and Arthur Keith (1864–1944) in east Tennessee. Within 20 years, these men published geologic maps of twenty-five 30-minute quadrangles in the Survey's folio series and worked on the geology of several more. Out of this mapping, which was more detailed than any previously done in the Appalachians south of Pennsylvania, several new ideas about Appalachian structure developed.

Probably the most fruitful general result of this work was the discovery by Hayes[14] of thrust faults exhibiting low dips (with the fault surface commonly warped) and great lateral displacement, a type not recognized before in the Appalachians. Such faults have now been found in many parts of the southern Appalachians and also in the northern Appalachians, though there they are of earlier date and argument still rages over many specific examples. In the folded middle Appalachians (omitting the controversial southeast margin), the structure is apparently simpler and large low-angle faults have nowhere been recognized. Nevertheless, the faulted area on the Nittany anticline at Birmingham, Pennsylvania, as described by Butts,[15] strongly suggests low-angle faulting to a geologist who has worked among the low-angle thrust faults of east Tennessee.

Hayes believed that the low-angle thrust faults he described were formed later than the folds and lesser thrust faults of the area, and one of them he conceived to have ridden forward over the deeply eroded crest of an anticline. For this fault he coined the term erosion thrust; the concept seems to have been incorrect for the fault to which he originally applied it, but it has been used with success in areas other than the Appalachians.

During this same period of mapping, Campbell[16] discovered in Virginia what he thought was evidence of striking unconformities in the Paleozoic series and hence of strong early and middle Paleozoic folding. Not until many years later did he recognize that he had been studying one of the largest of the low-angle

[14] C. Willard Hayes, "The Overthrust Faults of the Southern Appalachians," *Bull. Geol. Soc. America*, Vol. 2 (1891), pp. 141–52.
———, "Geology of a Portion of the Coosa Valley in Georgia and Alabama," *ibid.*, Vol. 5 (1894), pp. 465–80.

[15] Charles Butts, "Geology and Mineral Resources, Tyrone Quadrangle," *Pennsylvania Geol. Survey*, 4th Ser., A96 (1939).

[16] Marius R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Bull. Geol. Soc. America*, Vol. 5 (1894), pp. 171–90. Retracted in *Virginia Geol. Survey Bull. 25* (1925), pp. 56–96.

thrust faults. Keith followed Campbell at first, mistaking faults for unconformities and as a result mixing much of Safford's excellent stratigraphy, but later he reversed himself and announced[17] the discovery of low-angle thrust faults as large as those of Hayes, on one of which the pre-Cambrian basement has been carried for miles out over younger rocks. This discovery appeared to prove that the low-angle faults were different in kind as well as in degree from the high-angle thrust faults previously recognized, many of which, as the Rogers brothers had noted, seem to have developed out of asymmetrical anticlines by breaking across the steeper limb. In contrast to Hayes, Keith believed that at least this fault was the first product of the main Appalachian deformation and that it was itself folded and faulted in a later phase of the deformation.

In the meantime, Willis attacked the theoretical implications of Appalachian structure.[18] On the basis of experimental models, he developed the concept of competence of sedimentary strata, an idea of general application in structural geology. His experiments also suggested to him that the contrast between the folded middle and faulted southern Appalachians resulted from a difference in thickness of overburden on the most competent stratum at the time of deformation, and that the individual folds and faults were localized by initial dips produced by unequal sedimentation in the geosyncline. These two ideas are stimulating and plausible but they remain unproved, for the experiments on which they were based were inadequate because the strength of the materials used was many times too great to serve as a scale model. The second of the two ideas seems inapplicable to the Appalachians, however well it may work elsewhere, because it fails to explain the remarkable length, linearity, and parallelism of most of the Appalachian structural trends. Willis and the others believed that all the deformation was the result of tangential forces, but Willis held for many years that the forces acted from the northwest, hence that all Appalachian folds and faults, excepting presumably the Murphrees Valley anticline, are underthrust.[19]

On the basis of the unconformities postulated by Campbell and Keith, Willis and his co-workers held for some years that folding recurred several times during the Paleozoic, though strongest at the end. This idea was further elaborated by E. O. Ulrich[20] (1857–1944), who maintained that deformation progressed very

[17] Arthur Keith, "Roan Mountain, Tennessee-North Carolina," *U. S. Geol. Survey Geol. Atlas Folio 151* (1907). First announced in *Science*, New Ser., Vol. 15 (1902), pp. 822–23.

[18] Bailey Willis, "The Mechanics of Appalachian Structure," *U. S. Geol. Survey 13th Ann. Rept.*, Pt. 2 (1893), pp. 211–81.

Bailey Willis and C. Willard Hayes, "Conditions of Appalachian Faulting," *Amer. Jour. Sci.*, 3d Ser., Vol. 46 (1893), pp. 257–68.

[19] Bailey Willis, *op. cit.;* retracted in *Science*, New Ser., Vol. 25 (1907), p. 867. For a general summary of the conclusions of the group, see Arthur Keith, "Outlines of Appalachian Structure," *Bull. Geol. Soc. America*, Vol. 34 (1923), pp. 309–80.

[20] E. O. Ulrich, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. America*, Vol. 22 (1911), pp. 281–680. The trough and barrier idea was first set forth by E. O. Ulrich and Charles Schuchert, "Paleozoic Seas and Barriers in Eastern North America," *New York State Mus. Bull. 52* (1902), pp. 633–63, but it should be recorded here that in his later years Schuchert abandoned the idea as applied to the middle and southern Appalachians (personal communication, 1940).

slowly across the Appalachian region from southeast to northwest. Thus in early Paleozoic time the severe deformation was confined mostly to areas southeast of the present folded and faulted belt, in which its only result was gentle folding of the floor of the geosyncline into narrow subparallel troughs and barriers. Late in the Paleozoic the deformation reached and elevated the western part of the Piedmont, giving rise to the thick clastic sediments of the Pennsylvanian. Not until the middle Mesozoic did folding and faulting affect the present Valley and Ridge Province, while on the southeast the block faulting of the Triassic basins took place. The final low-angle thrust faulting Ulrich assigned to the Cenozoic. Few geologists to-day would thus extend the Appalachian orogeny over most of post-Cambrian time, but others have questioned its Permian date. Though the main deformation was almost certainly later Paleozoic, the possibility remains that it took place in a series of pulses affecting different parts of the chain at different times.

Since the folio work under Willis' direction, much geologic work has been carried on in the Appalachians, especially in the coal fields of the Appalachian Plateau. Probably the outstanding field geologist of this period was Charles Butts (1863–1946), who devoted virtually his entire life to Appalachian geology and whose work will form a basis for future investigators to build on from Pennsylvania to Alabama.

RECENT TRENDS

During the present century an important difference of opinion has slowly been developing among students of the Appalachians, though often the protagonists have hardly seemed aware of it. The difference of opinion concerns the depth of the deformation; does it or does it not involve the basement? Until approximately 40 years ago, no one thought it necessary to argue the point; it seemed self-evident that the folds and faults continued downward through the sedimentary sequence into the pre-Cambrian. Apparently the first conscious argument in favor of this view was by George H. Ashley,[21] who, discussing Willis' idea that a competent stratum in an anticline supports the overlying incompetent beds, described a low arch in the Appalachian Plateau of Pennsylvania in which no bed could have supported even itself without far surpassing the crushing strength of any rock known. According to Ashley, therefore, all the beds must have been supported from below. More recently Sherrill,[22] in a careful discussion of the folds of the plateau region, amplified Ashley's arguments and added others, tending to show that all those folds must have been continually supported from the basement. Neither Ashley nor Sherrill dealt with the possible application of this idea to the much steeper folds of the Valley and Ridge Province.

[21] George H. Ashley, "Studies in Mechanics of Allegheny Structure," *Science*, New Ser., Vol. 27 (1908), pp. 924–25.

[22] Richard E. Sherrill, "Symmetry of Northern Appalachian Foreland Folds," *Jour. Geol.*, Vol. 42 (1934), pp. 225–47.

This application has been made, however, by Nevin and especially by Ver Wiebe,[23] who argued from the limited strength of rocks, from the outpost position of such large folds as the Nittany and Sequatchie anticlines, and from certain hypotheses about the development of the geosyncline that the core of each major anticline and the upthrown side of each major thrust fault in the Appalachians is supported by an upwarp or upthrow in the basement. In other words, the major deformation took place in the basement, and the sedimentary strata are merely draped over it.

The opposite view also took form slowly. In 1921, Wentworth,[24] working on a suggestion from M. R. Campbell, recognized that a peculiar belt of faulting and crushing in Dickenson and Buchanan counties in southwest Virginia completes the outline of a great quadrilateral block (first recognized by Safford), the northwest side of which is formed by the Pine Mountain thrust fault, and the whole of which has been pushed several miles northwestward. Wentworth realized that the Pine Mountain fault has a low dip but apparently assumed that it continues indefinitely downward across the strata. In 1927, Butts[25] announced the discovery of several windows in the thrust block more than 15 miles southeast of the Pine Mountain fault, proving that, far from descending to the basement, the fault remains at a shallow depth for many miles southeastward.

In 1934, John L. Rich[26] presented a plausible mechanical interpretation of this fault, based on the concept that it developed largely along the bedding of the weakest formations in its path, and he suggested that the other Appalachian thrust faults may likewise follow bedding planes at shallow depths for many miles southeast of their present traces and that the basement beneath the faulted belt may be quite undisturbed. Faults of this kind would not be simply broken anticlines; on the contrary, Rich showed that many of the folds may rather be the result of the faulting. Moreover, the distinction between high-angle and low-angle thrust faults falls away, for the same fault may be high-angle and low-angle at different points down the dip. In recent years, increasing study of the low-angle thrust faults of the southern Appalachians has converted most of us now working in that area to views much like those of Rich. Indeed Ralph Miller,[27] in a recent abstract, has suggested as one possibility that all the thrust faults in

[23] Charles M. Nevin, *Structural Geology*, 1st ed. (1931), pp. 54, 62; 2d ed. (1936), pp. 55–57, 65–66; 3d ed. (1942), pp. 50–53, 59–60. John Wiley and Sons, New York.
Walter A. Ver Wiebe, "Geosynclinal Boundary Faults," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20 (1936), pp. 910–38.

[24] Chester K. Wentworth, "Russell Fork Fault of Southwest Virginia," *Jour. Geol.*, Vol. 29 (1921), pp. 351–69; *Virginia Geol. Survey Bull. 21* (1921), pp. 53–66.

[25] Charles Butts, "Fensters in the Cumberland Overthrust Block in Southwestern Virginia," *Virginia Geol. Survey Bull.* 28 (1927).

[26] John L. Rich, "Mechanics of Low-Angle Overthrust Faulting as Illustrated by Cumberland Thrust Block, Virginia, Kentucky, and Tennessee," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18 (1934), pp. 1584–96.

[27] Ralph L. Miller, "Relation of Overthrust Faults in Southwest Virginia," *Bull. Geol. Soc. America*, Vol. 56 (1945), pp. 1182–83.

southwest Virginia and east Tennessee may be branches of a single nearly flat sole fault.

Another current controversy, which in some respects runs parallel with the one just discussed, concerns the width and eastward extent of the belt that developed into a geosyncline during the Paleozoic and was deformed in the Appalachian orogeny. According to what is perhaps the traditional view, widely held among those who believe that folds continue to the basement and championed in an extreme form by Ver Wiebe,[28] the eastern margin of the geosyncline lay close to the present northwest edge of the crystalline rocks of the Blue Ridge and Piedmont. Thus, the geosyncline coincided almost exactly with what is now the belt of folded and faulted but unmetamorphosed rocks, and this belt was the principal locus of the late Paleozoic deformation. The opposite view[29] holds, on the contrary, that large bodies of the schist in the Piedmont are Paleozoic, as much of the corresponding schist in New England is now known to be. On this view, the present folded and faulted belt represents not the deepest part of the Appalachian geosyncline but merely a northwestern and lesser (*mio*geosynclinal) part. Similarly, the structure of the Valley and Ridge Province, mammoth as it is, is only marginal deformation (the term is Bucher's) with respect to the main Appalachian deformation recorded in the metamorphic and igneous rocks on the southeast. The decision between these two views must await long years of detailed and painstaking work among the crystalline schists of the Piedmont.

Thus, the natural development of ideas has led at length to two very different concepts of Appalachian structure, which may perhaps be characterized as the "thick-skinned" and the "thin-skinned" schools of thought.[30] The thick-skinned geologists, most of whom have worked chiefly in the middle Appalachians and the flat-lying rocks of the Appalachian Plateau or farther west, have reasoned from the broad low folds of the plateau to the hypothesis that the folds and faults of the Valley and Ridge Province are the main manifestation of the Appalachian orogeny and that each continues separately to the basement. The thin-skinned geologists, most of whom have worked chiefly in the highly faulted southern Appalachians, have reasoned from the great low-angle thrust faults of that area,

[28] Walter A. Ver Wiebe, *op. cit.*

[29] This view has been suggested by several writers, for example:
Walter H. Bucher, *The Deformation of the Earth's Crust*, pp. 149–61. Princeton (1933).
Marshall Kay, "Geosynclines in Continental Development," *Science*, New Ser., Vol. 99 (1944), pp. 461–62.
But the first detailed application known to the present writer is that by Ernst Cloos in his contribution to the present symposium:
Ernst Cloos, "Structures of Basement Rocks of Pennsylvania and Maryland and Their Effect on Overlying Structures" (abstract), *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 11 (November, 1948), p. 2162.

[30] These terms recall the distinction drawn by Rollin T. Chamberlin in "The Building of the Colorado Rockies," *Jour. Geology*, Vol. 27 (1919), pp. 145–64, 225–51 (esp. pp. 248–51; *cf.* also *ibid.*, Vol. 29 (1921), pp. 166–72) between thick-shelled and thin-shelled mountain ranges, but although Chamberlin classed the Appalachians as a thin-shelled range, he believed that the deformation affected the crust to a depth of 6–30 miles (see *Jour. Geol.*, Vol. 18 (1910), pp. 228–51), so that he may definitely be classed in the "thick-skinned" school.

especially the Pine Mountain fault, to the hypothesis that the Paleozoic rocks of the unmetamorphosed part of the Appalachians, caught on the margin of intense deformation on the southeast, were stripped completely off the basement and piled up against the unyielding plateau in great rootless folds and imbricate thrust sheets underlain by a few bedding-plane faults of immense displacement. The two schools of thought have gone almost as far as they can at present in setting forth the rival hypotheses and deducing their implications. It is time now to confront these hypotheses with facts.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1655-1681, 8 FIGS.

REGIONAL ASPECTS OF CAMBRIAN AND ORDOVICIAN SUBSURFACE STRATIGRAPHY IN KENTUCKY[1]

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ABSTRACT

Suggestions are made for correlation of Cambrian penetrated in the deeper wells in Kentucky with the outcrop on the Ozark uplift and with the sections on the north. Thickness maps indicate (1) the overlap of older Knox formations by younger members of the Chazyan on the north, and (2) the unconformity at the top of the Cincinnatian with loss of younger formations toward the Ozark uplift.

Stratigraphic sections are used to indicate lithologic changes through the major divisions of the Ordovician. The pattern of these facies suggests that the extended Ozark uplift was a source for much of the clastic sediments from the Chazy to the close of the Cincinnatian. A sub-Cretaceous areal geologic map is presented to show the probable extent of that part of the uplift now buried beneath the more recent sediments of the Mississippi embayment.

INTRODUCTION

This paper is not presented as a finished work on the Ordovician system in Kentucky. No detailed studies have been made by the writer on the section between the Knox dolomite and the Silurian, but in examining samples from deep wells the Ordovician lithology has been logged so many times that a regional picture has emerged. It is hoped that these generalizations on Ordovician stratigraphy through the western part of the Appalachian basin may be useful to those stratigraphers who have already made contributions in detailed work elsewhere.

Examination of papers presented at the Ordovician symposium[3] indicates that the general conception of the Appalachian basin is one with its western border formed by the Cincinnati arch. Lithologic and stratigraphic studies made through Kentucky and Tennessee indicate that part of the Cincinnati arch had less effect upon sedimentation and preservation of sediments during the Ordovician than did the Ozark uplift.

A more accurate picture may be formed of the sedimentary problems of these older formations if this whole area is considered a continuous basin of deposition locally affected by positive areas such as the Ozark and Laurentian highs.

A study of the distribution of the Cambrian and Ordovician in Kentucky indicates that at no time during these periods did the Cincinnati arch act as a positive feature, or materially affect distribution of sediments. It was not until

[1] Read before the Association at Pittsburgh, October 5, 1948. Manuscript received, March 11, 1949.

[2] Consulting geologist. Many of the data on the Knox dolomite were gathered while working on projects for The California Company and the writer is grateful for the opportunity to study them. The personnel of the Missouri, Kentucky, and Tennessee geological surveys have been extremely cooperative in making the samples from the wells in their respective states available. Samples have been borrowed from many companies operating in all of the surrounding states and their aid is greatly appreciated.

[3] Sponsored by the Pittsburgh Geological Society on May 16, 1947; published in *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 8 (August, 1948).

Middle Silurian that the character of the formations was affected and finally that erosion took place.

Charles W. Wilson, Jr.,[4] suggested that a structural connection existed between the Nashville dome of the Cincinnati arch and the Ozark dome. The

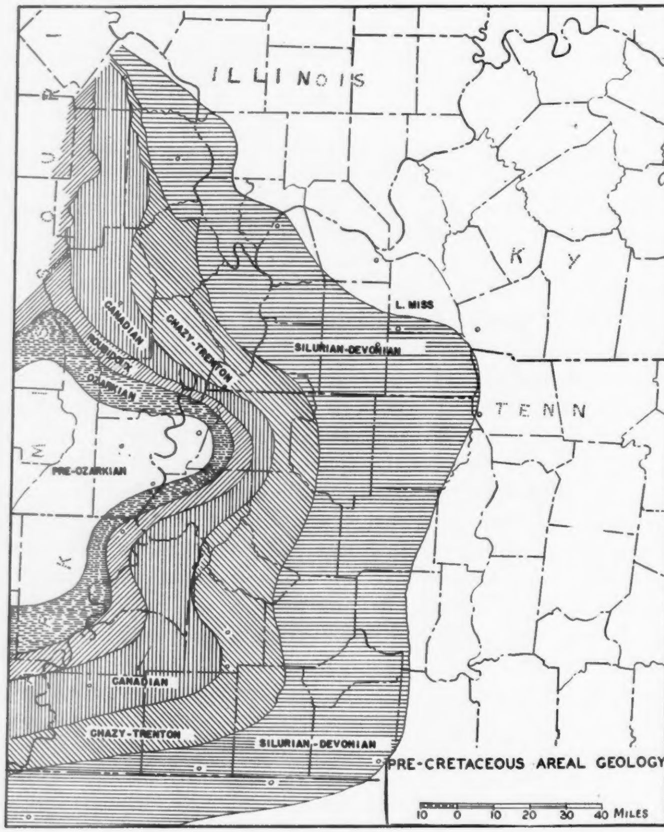


FIG. 1.—Pre-Cretaceous areal geology.

present writer[5] indicated a subsurface high between the Nashville dome and the Ozark uplift, now buried beneath Cretaceous and Tertiary sediments of the

[4] Charles W. Wilson, Jr., "Probable Connection of the Nashville and Ozark Domes by a Complementary Arch," *Jour. Geol.*, Vol. 47, No. 6 (1939), pp. 583–97.

[5] Louise Barton Freeman, chapter on "Paleozoic Geology" in "Geology and Mineral Resources of the Jackson Purchase Region, Kentucky," by Joseph K. Roberts and Benjamin Gildersleeve, *Kentucky Dept. Mines and Minerals*, Ser. 8, Bull. 8 (1945).

Mississippi embayment, thus furnishing subsurface evidence of Wilson's structure. This high was postulated on the basis of a few wells drilled in western Kentucky and Tennessee. Further study of well samples in Missouri, Arkansas, Tennessee, and northern Mississippi served to verify the high area and to indicate that it is not a separate structure, but a nose southeastward from the present Ozark uplift.

Frederic F. Mellen[6] arrived at essentially the same conclusions in his report on the Black Warrior basin.

The sub-Cretaceous areal geology of a part of the embayment, indicating the extent of the earlier uplift, is shown in Figure 1. Cretaceous gravels in Ballard and McCracken counties rest on Lower Mississippian cherty limestones and shales. The Cretaceous directly overlies the Chattanooga black shale in Trigg County, the Clear Creek chert of the Middle Devonian in Marshall County, the Bailey chert of the Lower Devonian in Graves County, the Trenton limestone of the Ordovician in northeastern Fulton County, the Stones River of the Ordovician in southern Fulton County, and Middle Cambrian trilobites were recovered from cores of a well in northwestern Tennessee.

Southward the pre-Cretaceous areal pattern is equally well defined by the broad outcrop pattern of the Devonian in the Tennessee Valley and as far west as the northwestern corner of Mississippi. If the distribution of the Paleozoic rocks is extended to the west side of the embayment, the pattern fits well with the outcrop in the Ouachitas.

CAMBRIAN

Thus far in the study of subsurface Knox dolomite, no appreciable break has been recognized in the entire Knox section. Correlations of parts of the section can be made but nowhere is there evidence of orogeny and a long period of erosion in the Cincinnati arch area. At the close of the Knox, however, there was a major break resulting in a marked change in the relations of land areas to basins of deposition. It is extremely difficult for a student of subsurface stratigraphy to see why a major systemic break should be inserted into a long sequence of siliceous dolomites, when a break of such importance occurs over a tremendous geographic area at the close of this period of accumulation. For purposes of interpreting the stratigraphic sedimentology in this paper the entire Knox section is considered as a unit and is referred to as Cambrian.

The lithologic units recognized in the Knox of the Ozarks can be traced into central Kentucky and Tennessee by means of well samples. Actual formational boundaries are not easily determined and it would be unwise to attempt close correlation over such a large area with such few data. It is possible, however, to recognize similarities of sequence. It should be remembered in making such correlations that the Ozark dome was subjected to influences that were slightly

[6] Frederic F. Mellen, "Black Warrior Basin, Alabama and Mississippi," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 31, No. 10 (October, 1947), pp. 1801–17.

different from those in the basin area, and these differences must be reflected in the lithologic character of the sedimentary rocks as well as the fauna.

Many wells have been drilled to the granite on the Ozark dome, and in the St. Francis Mountains the pre-Cambrian granites are exposed. One well has been drilled into granite on the south flank of the Nashville dome in Tennessee, and one well has been drilled into rhyolite porphyry, presumably pre-Cambrian, on

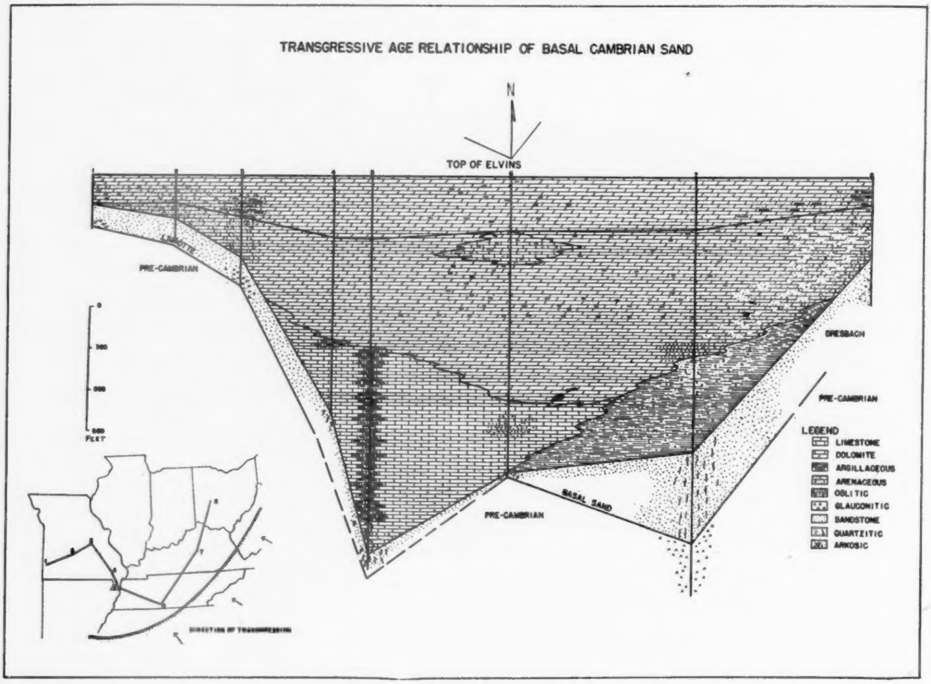


FIG. 2.—Stratigraphic sections showing basal sands.

the south flank of the Lexington dome[7] in Kentucky. At this time, it is more proper to speak of the separate domes rather than of the Cincinnati arch, which term carries with it a picture of the arch as it is to-day.

BASAL SAND

On all three domes there is a basal sand, but there is no evidence that these sands are age equivalents. The Cambrian seas moved from the south and southeast over an irregular surface. Whether the irregularities were entirely erosional

[7] The term, Jessamine dome, has been used by some writers, but since Lexington has more general meaning as a geographic entity, it might serve better for the purpose.

or partly due to vulcanism, as suggested by the rhyolite in the Spears well (well No. 69[8] and Fig. 2), there is insufficient evidence to determine at this time. Basal sands were deposited which were progressively younger northward.

Most of the Laurentian shield area, including the Wisconsin high, the Ozark uplift, and the entire area north along what is now the Cincinnati arch was subjected to erosion, the results of which accumulated in the gradually encroaching Cambrian sea. This relationship is indicated by a map showing direction of encroachment and stratigraphic sections showing approximate age relationships (Fig. 2). The area where the basal sands accumulated was a fairly stable shelf with the lands on the north and west low so that sand deposited was washed about and the mineral content sorted. Those sands coming to rest at some distance from the shore were size-sorted as well, but those near shore, as near the Ozark uplift, were poorly sorted. The Lamotte includes silt to coarse sand, the grains being angular to rounded.

The stratigraphic sections (Fig. 2) extend southeastward across the Ozarks into Tennessee, pivoting at the Beeler well (No. 174) and continuing northeastward, essentially along the present crest of the Cincinnati arch.

The basal sand in the Beeler well (No. 174) in south-central Tennessee is very thin, hardly more than a little residual sand from the granite, but it is older than the thicker basal sand in the Spears well (No. 69) in central Kentucky. The basal sand in the Spears well was fairly well sorted as to mineral content and size but was quartz-cemented. Both are considerably older than the basal sand (Lamotte) of the Ozarks. North of the Nashville dome, sands were being derived not only from local sources but were also being carried in from the northern land areas. Thus, clastics accumulated for a long period of time in the Lexington dome area while dolomites were being deposited offshore over the Nashville dome, and dark argillaceous limestones from organic calcareous oozes were collecting basinward, not only southeastward but also in the quiet waters south of the Ozarks. By this time the Ozarks were very low, and argillaceous limestone was deposited on the south while granites were being eroded and the quartz accumulating as lag sand to form the Lamotte.

The Central Interior, north of the Nashville dome and the Ozarks, was still being eroded while the basal sand accumulated over the Nashville dome and southward. While the basal sand was being deposited over the Lexington dome, the Nashville dome and the area southward were receiving limestone and the Ozarks were still being eroded. While the Ozarks were receiving sand deposition, directly southward in the basin, argillaceous limestones were being deposited, and dolomite was being formed on the Nashville and Lexington domes.

The basal sands north of the Lexington dome should be even a little younger than those in the Ozarks. These sands were being deposited nearer the shore of the slowly encroaching sea, while finer clastics were deposited farther from the source, giving rise to the very silty and slightly calcareous shales, rich in glauco-

[8] Well numbers are shown on the thickness maps.

nite, found above the sand on the Lexington dome (well No. 69). These shales, similar to the Rome in origin, must have been deposited later than the Rome but also earlier than the Nolichucky which is here represented by dolomite. Thus, if the sea gradually moved inland, north and west, the near-shore deposits were sand, offshore deposits were silty and glauconitic shales, and basinward dolomite and limestone accumulated. This lithologic sequence then would be time transgressing, becoming younger northwestward.

In Kentucky, immediately following shale and silt deposition in the early Cambrian, oölitic limestones and dolomites accumulated before complete dolomite deposition began. A similar situation existed in the Ozarks southeast of the present uplift, when oölitic limestones formed offshore from the basal sands and onshore from the argillaceous limestones. These oölitic limestones and dolomites in the Lexington dome area would represent the offshore facies of the basal sands farther north and thus should be approximate age equivalents of the Dresbach.

The Nashville dome was probably always a little more of a positive feature than was the Lexington dome, perhaps due to its actually being a part of the strong Ozark high.

By the time the seas had covered the Ozarks and moved northward, all three domes were sufficiently positive to form broad shelves to receive dolomite deposition. Shoreward, on the north and northwest, much sand was deposited with the dolomite. Some of this sand was carried as far south as Kentucky, commonly as floating sand grains, but rarely accumulated into lenses. Much of the silica was in solution and was deposited as chert. In general there is more sand in the upper part of the Knox on the west side of the Lexington dome than on the east side, just as there is more in the Ozark area than anywhere on the east. There is an increase in sand content toward the northwest, suggesting a source in that direction. Basinward the deposits were mainly limestones and interbedded dolomites, Appalachia by this time being too low to contribute much in the way of clastics as far west as the present mountain front.

With this history in mind, the difficulties of establishing horizon-markers from one area to another in the Knox can be appreciated.

BONNETERRE

In the Ozarks the Bonneterre overlies the Lamotte basal sand and in places rests directly on pre-Cambrian granites (Fig. 2). It is dolomite, medium to coarse crystalline, white to pale gray, and relatively free from shale excepting a few streaks of very fine, green clay, and relatively free from silt and sand. It does include, however, quantities of glauconite in sand-sized nodules, in contrast to the silt-sized glauconite of the overlying Elvins.

Wells drilled on the southeast, in western Tennessee and Arkansas, show not only a change in facies basinward but also a thickening of the section due to the addition of older Cambrian, not deposited over the high. The position of the dolomite is occupied by fine, argillaceous, dark limestone, and the thickening below

the top of the Bonneterre ranges from 260 feet in Hickory County and about 500 feet in Washington County, Missouri, to 2,400 feet without penetration of the granite in Pemiscot County, Missouri, on the southeast. This change in facies occurs in a relatively short distance, and similar changes, in minor form, might be expected off the Nashville dome.

In Kentucky the Bonneterre is dolomite, essentially as uncontaminated by silt and shale as in the Ozarks, but glauconite is not found in such large quantities. Farther north, where this interval is occupied by the Franconia sandy dolomite, glauconite is common.

ELVINS

The Elvins group of the Ozarks contains some silts, shales, and sands here and there associated with the dolomite, but is characterized by the association of fine quartz silt with glauconite grains of approximately silt size. It is overlain by the Potosi cherty dolomite, and underlain by essentially non-cherty but very glauconitic Bonneterre dolomite. In all of the wells drilled deep enough in Kentucky, the sequence was similar, with a sandstone, the areal extent of which is not well defined, in the Elvins of the Cincinnati arch. This sand is locally called the Rose Run because it was first noted in a well (well No. 11) drilled on the Rose Run hematite properties in Bath County, Kentucky. As in the Bonneterre, there is not as much of the glauconitic silt in the Elvins of Kentucky, but on the north the Trempealeau has the same sort of glauconite silt but has even more sand than is found in the Ozarks, excepting locally where the Davis member is a good sandstone similar to the Rose Run of Kentucky.

POTOSI

The Potosi of Missouri is distinctive crystalline dolomite with tendency toward more brown color and with characteristically drusy chert. The drusy chert of the Potosi seems to have been deposited, possibly from magmatic waters, during the time of mineralization of fractures. There was some fracturing with mineralization on the Lexington dome, shown by mineralized veins and by the development of the drusy chert. The Lexington dome, however, was less of a positive feature than the Ozark dome, and was not subjected equally to the strains which resulted in such fracturing, recrystallization, and mineralization. Thus, quantitatively there is considerably less of the chert in the Kentucky wells. They do, however, show in the proper sequence a series of brown crystalline dolomites with traces of the drusy chert, overlying dolomite that is not cherty but which does have traces of quartz and glauconite silt (Elvins).

EMINENCE

The Potosi is followed throughout the Cincinnati arch area by dolomite that is pale gray, fine to coarse crystalline, with only traces of gray, quartzitic chert. It is much less siliceous than dolomite either above or below it. This lithologic character is typical of the Ozark Eminence formation.

VAN BUREN-GASCONADE

The Eminence with its low silica content is overlain by light-colored, medium crystalline dolomite with considerably more chert. The Van Buren-Gasconade chert is in general dense white to translucent, with some thick-walled dolomolds and irregularly shaped oölites. The upper contact is more sharp than for many Knox formations due to contact with the sandy Roubidoux.

CANADIAN

The basal Canadian, the Roubidoux formation, in the Ozarks contains much sand, rounded and frosted, some of which is chert-cemented. Detailed descriptions of the various units of the Canadian are not given here.[9] In general, the dolomites are finer-grained than the older formations of the Knox, more clastic in character, with some fine silts, floating sand grains, and rare, fine green shales. The cherts are more oölitic and dolomoldic than those below.

The Canadian has been subdivided into the Roubidoux, Jefferson City, Cotter, Powell, *et cetera,* which formations locally have lithologic characteristics by which they can be differentiated. In Kentucky a series of dolomites having the same characteristics as the Canadian in the Ozarks can be recognized. In many wells the characteristic insoluble residues of the Roubidoux, Jefferson City, and Cotter units of that series can be seen in proper sequence. In all wells drilled sufficiently far into the top of the Knox there is a unit about 150 feet thick characterized by very sandy chert similar to the Roubidoux. This overlies the heavily siliceous Gasconade.

Basinward in the Canadian there is more interbedded limestone with the dolomite. Thus, in the deep well in south-central Tennessee (California Company's Beeler No. 1) there is considerably more limestone in that part of the section than there is on the Lexington dome, and the Beekmantown of Virginia contains more limestone at the outcrop than is found in wells in Kentucky.

CLOSE OF KNOX

At the close of Knox time the Ozarks again became positive and the high areas on the north were again exposed to erosion.

Figure 3 shows thickness of the post-Elvins Knox in Kentucky. This thinning is by erosion of the upper formations, although a little may be due to nondeposition if the uplift in the Laurentian area began before the close of Knox time. Central Kentucky, near the crest of the present Cincinnati arch, has up to 1,700 feet of post-Elvins Knox as compared with less than 100 feet about 50 miles northeast. The map indicates (Fig. 3) two more such isopachous highs suggestive

[9] The descriptions of the Knox formations in this report consist only of the characteristics which have been most helpful in establishing correlations from the Ozarks to the Cincinnati arch area. More detailed descriptions of these formations and their insoluble residues are given in the following publication: H. S. McQueen, *Biennial Report of the State Geologist,* Missouri Bureau of Geology and Mines (1931), Appendix I.

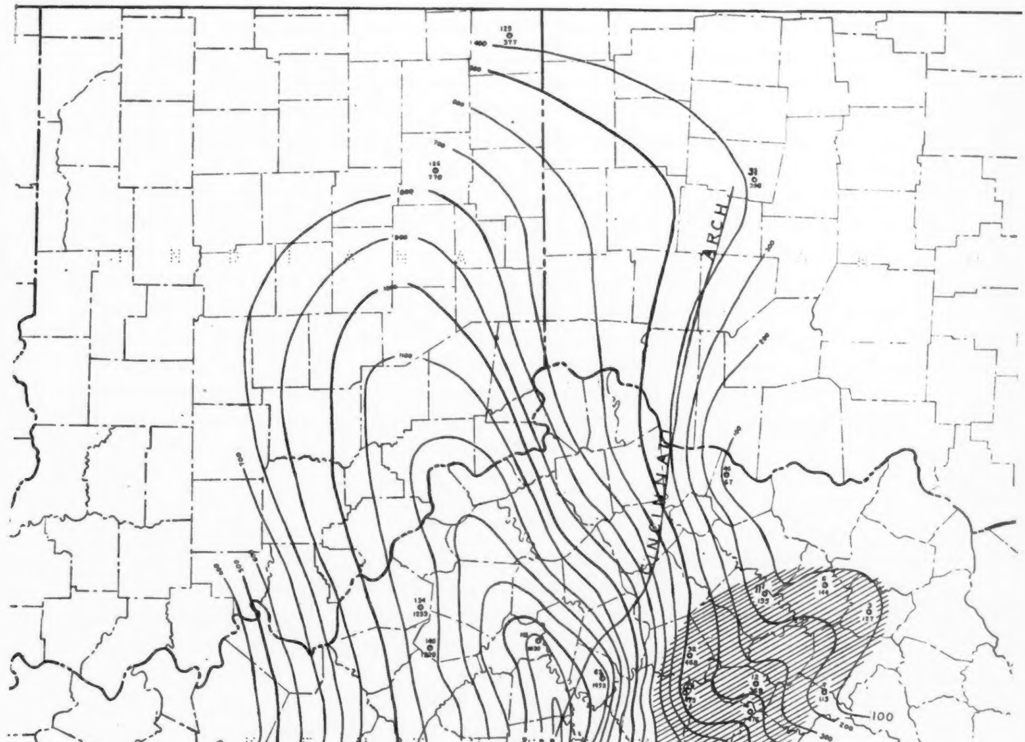


FIG. 3.—Map showing thickness of post-Elvins Knox.

of the trend of the Cincinnati arch. This alignment of thicker areas may be the series of irregularities responsible for localization of the arch.

In Kentucky only about ten wells have been drilled into the Knox as much as 1,000 feet. Most of the data in this map (Fig. 3) were obtained from correlations of short sections. Future drilling with additional information may change this picture.

Uplift on the north resulted in thinning of the section in that direction. Uplift on the southwest resulted in thinning in that direction. It is unknown why there should have been thinning southeastward.

The hachuring indicates the known areal extent of the Rose Run sand. Apparently it coincides with the axis of thinning of late Knox formations. This may be only an apparent coincidence, however; though there is some control on the south and ample control on the west, there is none on the east and north. This sand is probably a southern extension of one of the Trempealeau or Franconia sands. A well drilled north of the indicated area probably would encounter it.

ORDOVICIAN

BEGINNING OF CHAZY

Following this period of uplift and erosion, the seas came from essentially the same direction as had the early Cambrian seas. The land area now was low, with sediments being eroded instead of basement igneous and metamorphic rocks; thus, the character of the deposits was different. The early Chazy sediments reflect this condition.

The coincidence of patterns made by the thickness map on the St. Peter is shown in Figure 4, the distribution of St. Peter in Figure 5, the thinning of post-Elvins Knox in Figure 3, and the distribution of, or at least the southern extent of, the Rose Run sand in Figure 3. There seems to be a definite east-west trend through eastern Kentucky. This was probably the hinge-line between the more stable basin of deposition of the Appalachians on the south and the unstable platform of deposition on the north. Thus, the sands of the Trempealeau were scattered generally over the unstable shelf with distribution running out southward. The relative uplift of the Laurentian area resulted in erosion of upper Knox formations. This uplift was hinged in the same general trend as the area through eastern Kentucky outlined by distribution of the St. Peter sandstone, which area was closely related to the shoreline for a short period. The St. Peter sand, derived from erosion of the Knox sandy dolomite, was deposited offshore for only a short distance. Relief of the shoreline was not great; the shoreline itself shifted considerably; the supply of sand was small. The distribution of the sand as found to-day in Kentucky, as a result of these factors, is limited areally to the area of abrupt thinning of upper Knox. Offshore, on the south, the finer products of solution collected to form the fine, argillaceous, dolomitic limestone of the basal Chazy (Murfreesboro).

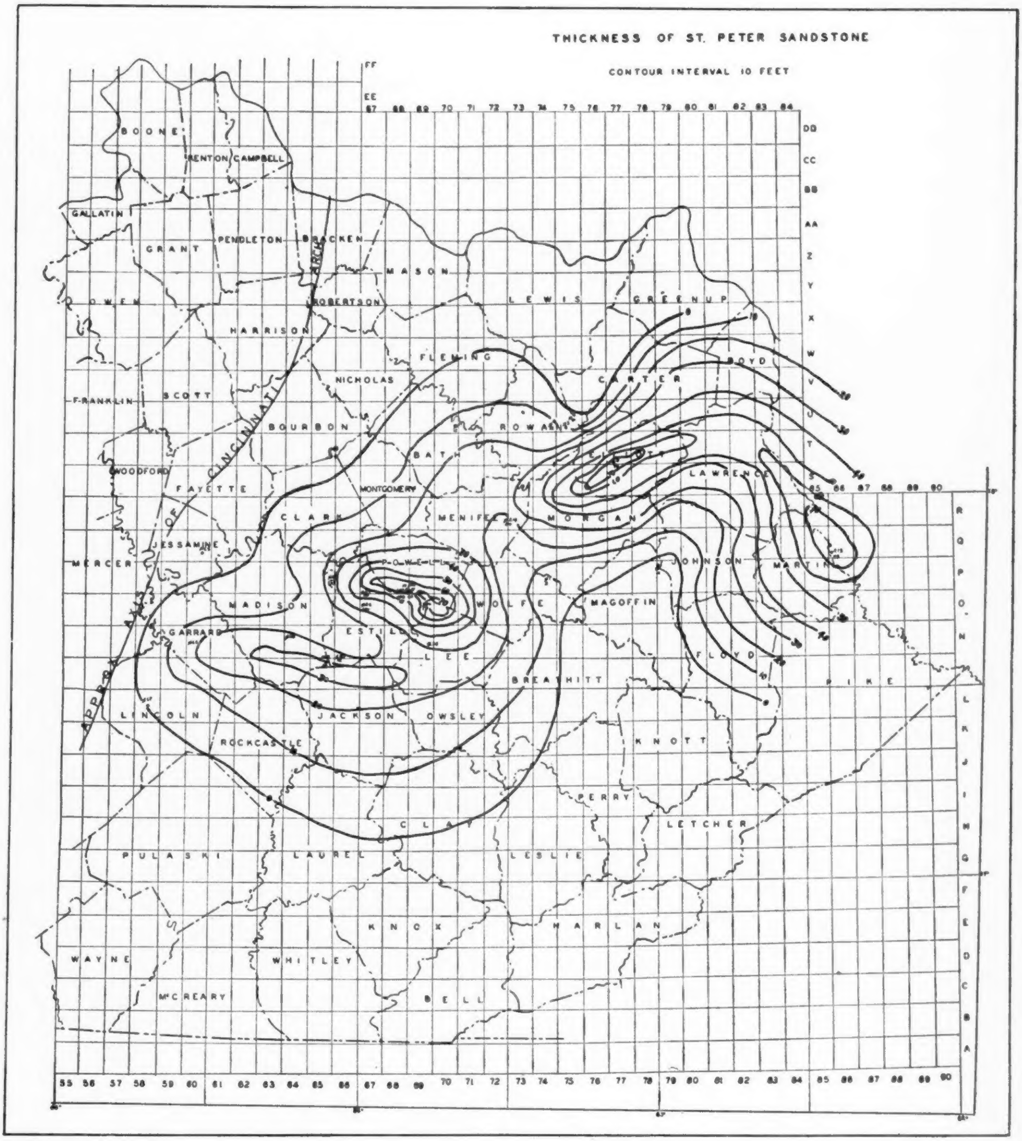


FIG. 4.—Map showing thickness of St. Peter sandstone.

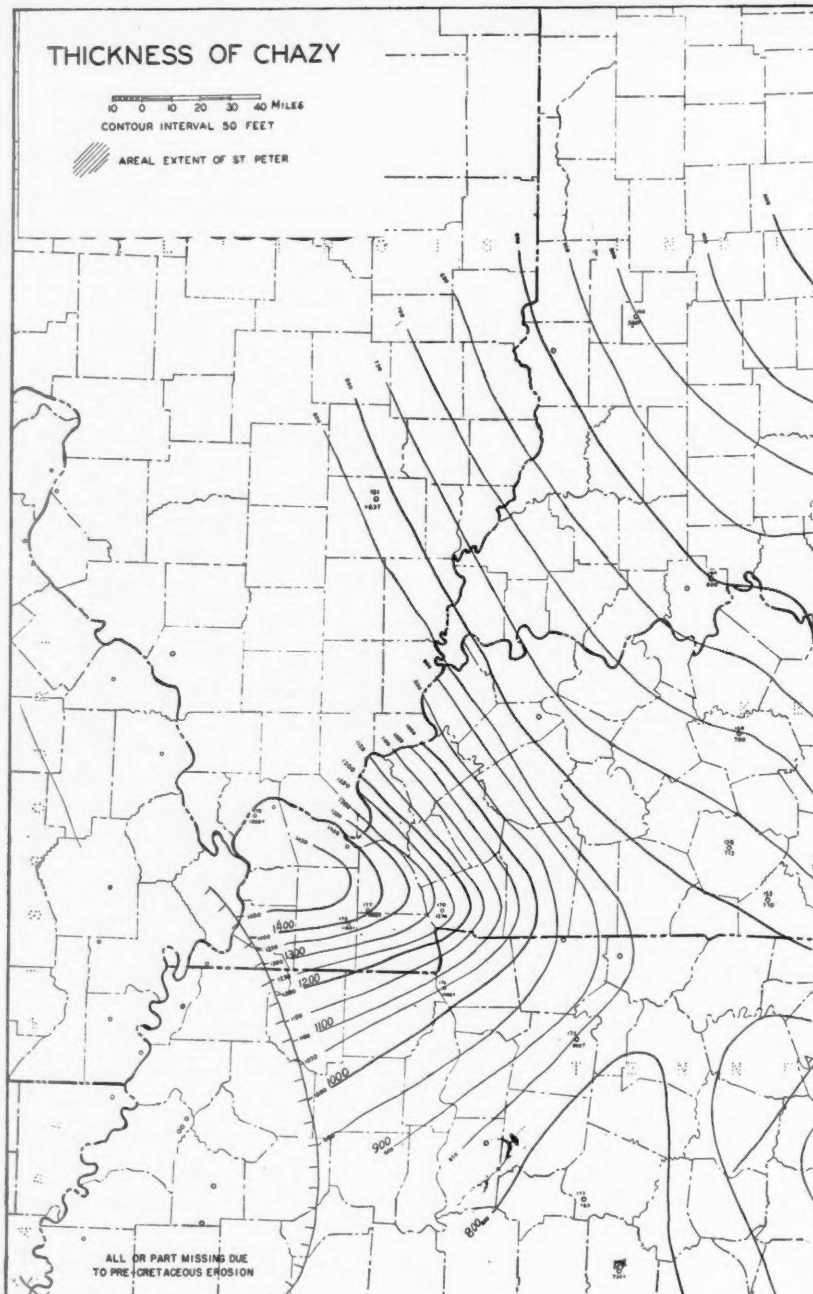
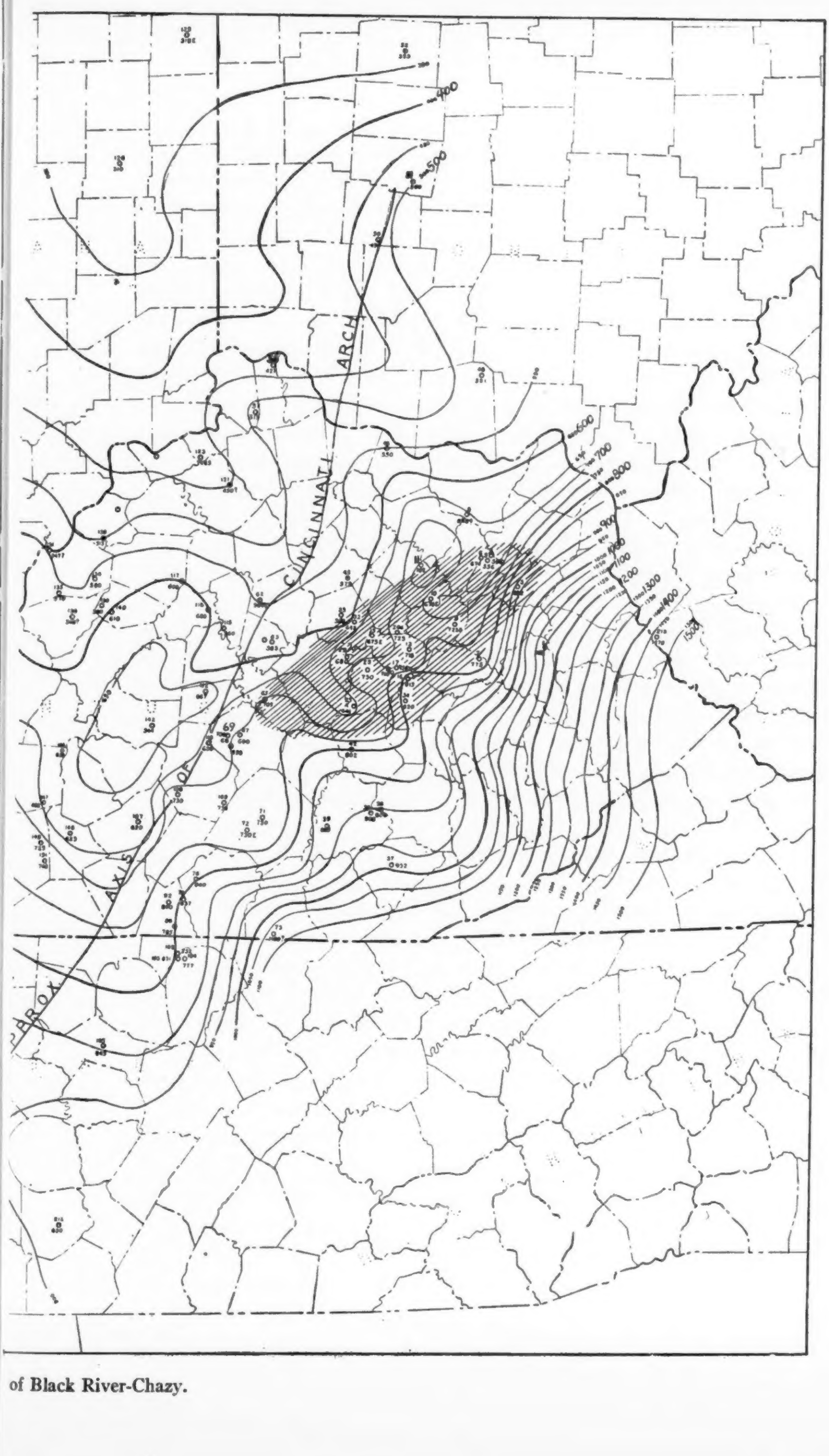


FIG. 5.—Map showing thickness



ness

of Black River-Chazy.

CHAZY-BLACK RIVER

Waters over the southern Cincinnati arch area were shallow and quiet, and sediments were calcareous oozes which resulted in the vaughanitic limestone of the Chazy-Black River. Around the Ozarks-extended, erosion of the upper Knox resulted in thick accumulations of clastic dolomite, silt, sand, and shale, known as Buffalo River and Dutchtown. As during the Middle Cambrian, when argillaceous limestones were deposited south of the uplift while dolomite formed across the high, so during this early Ordovician the same area on the south received similar dense, argillaceous limestone, the Smithville-Black Rock. During most of Chazy-Black River time the Ozarks remained high. It was only near the end of that period that the deposition of sublithographic limestone extended to and possibly over the uplift. In Tennessee, north of the suggested connection between the two domes, sediments of the Buffalo River facies were deposited, Wells Creek of Tennessee, but these thinned rapidly southward and were displaced by fine limestone.[10]

The Laurentian area, being lower, resulted in accumulation of the solution products of dolomite and limestone. Thus, fine-grained, green, argillaceous limestone was deposited to form the Glenwood. Kentucky, between these two areas, has elements of both types of sedimentation. On the west, the Buffalo River facies is paramount but decreases with distance from the Ozark high. Where Knox sand lenses were exposed, furnishing local sources, this sand was reworked and redeposited to form what has been called the St. Peter in Kentucky. Since there was less sand available for that purpose in the Knox of Kentucky, it is spotty in occurrence, as compared with the blanket but time-transgressing sand[11] of the type St. Peter where the entire Knox section contains considerably more sand.

The distribution of the St. Peter is indicated by hachuring in Figure 5 and there is sufficient control to be fairly certain of accuracy.

The thickness map of the interval between the top of the Knox and the top of the Tyrone (Fig. 5) shows thinning northward, with thickening southeastward into the deeper part of the Appalachian basin and southwestward toward the Ozark high. Thus, the period of uplift and erosion which resulted in irregularly thick areas of late Knox sediments, also, because of direction of re-encroachment and proximity to source of materials, affected a constant thickness of Chazy over these thick zones. This is another step in the formation of the Cincinnati arch.

It was suggested some time ago that the picture thus presented by an iso-

[10] Ray Bentall and Jack B. Collins, "Subsurface Stratigraphy and Structure of the Pre-Trenton Ordovician and Upper Cambrian Rocks in Central Tennessee," *Tennessee Div. Geol. Prelim. Chart 4*, Oil and Gas Inves. (1945).

[11] E. P. DuBois, "Subsurface Relations of the Maquoketa and 'Trenton' Formations in Illinois," *Illinois Geol. Survey Rept. Inves. 105* (1945).

J. G. Grohskopf, "Zones of Plattin-Joachim of Eastern Missouri," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 3 (March, 1948), pp. 351–65.

pachous map of this interval might also present a picture of Knox thinning, since it was known that thin Chazy rested on older and older formations into Ohio. Careful sample studies have shown this to be essentially true. Local structures developed during the pre-Chazy interval are likely to be reflected in local thinning of the Chazy.

Small irregularities which are apparent where there is a great deal of control have been omitted from this map to avoid confusing the regional picture. Undoubtedly if there were as many data for all of the state as there are for Estill, Powell, and Clinton counties, many more such local variations would be indicated.

Detailed studies made with this possible interpretation might reveal that the Smithville-Black Rock of Arkansas, the Buffalo River of the Ozarks, and the Chazy of the Appalachian basin are essentially correlative and mark deposits following an orogeny. Some faunal differences should be expected due to the difference in environment of deposition.

The post-Wells Creek Chazy of Tennessee, around the Nashville dome, contains a little more shale than do the equivalent formations north into Kentucky, as might be expected due to the proximity to the Ozark-extended high. The Murfreesboro and Pierce lose clay content on the northeast and can not be differentiated from the rest of the section in central Kentucky. Chert beds that can be used for correlation around the Nashville dome[12] are lost on the northeast in Kentucky where essentially the only chert in the Chazy or Black River is associated with bentonite.

In the Mississippi Valley, the basal Plattin[13] is marked by small structureless oölites—calcareous clay pellets and intraformational conglomerates—indicative of shallow-water conditions at that time. At nearly the same horizon similar oölitic zones are found in south-central Tennessee, that is, south of the Ozarks-extended, and in western Kentucky, north of that structure. These are limited to the region around the old high, however, and are not recognized basinward.

The section from basal Wells Creek to the top of the Carters in Tennessee, and the Camp Nelson-Oregon-Tyrone in Kentucky, is considered as a unit in subsurface work. There are no completely satisfactory units which would add important details to the regional geologic picture. Bentall and Collins[14] have broken this group into units which are a great convenience but only of local importance. At the outcrop, over the Lexington dome, a three-fold division is possible only because of the presence of a dolomitic limestone which occurs about 90 feet below the top of the Tyrone. This dolomite is undoubtedly secondary and related to the doming with development of fractures. It can be recognized in the subsurface only high on the structure. There is no evidence either on the surface or subsurface of a break in sedimentation in this part of the section.

[12] Bentall and Collins, *op. cit.*

[13] Grohskopf, *op. cit.*

[14] Bentall and Collins, *op. cit.*

In Kentucky the Chazy-Black River interval thickens from little more than 400 feet at the Ohio River to more than 1,100 feet in southeastern Kentucky and more than 1,400 feet in southwestern Kentucky where the clastic dolomites have been added to the base. The thinning can be explained almost entirely by non-deposition of the lower strata. It is a long sequence of vaughanitic to lithographic limestone with amazingly constant facies. Several thin metabentonites are known, the most persistent zone occurring within the top 20 feet of the Tyrone. This is the "Pencil Cave" of the drillers.

The changes of facies across Kentucky are indicated in the stratigraphic sections (Fig. 6). At the west end of the state the lower Chazy is composed of clastic dolomite, silt, floating sand, and some thin shale partings. This facies is gradually lost eastward, the lower part becoming darker and slightly more argillaceous than the upper 300 feet, corresponding with the Murfreesboro of Tennessee. Where the Chazy thickens southeastward it is by addition of older greenish gray, argillaceous limestones, and a little dolomite. In the area indicated by hachuring in Figure 5, on the east side of the present arch, the base is marked by the sandstone which is called St. Peter. Farther north the fine lithographic limestones may rest directly on the Knox, or the basal limestone may be slightly argillaceous and green, a southward extension of the Glenwood. The dolomitic limestones in the upper 100 feet of the section, previously mentioned, are limited to the top of the present Cincinnati arch.

TRENTON

The use of the term "Trenton" should be explained before that unit is described. According to common usage in Ohio and Indiana, the Trenton includes the limestone between the base of the Utica shale and the top of the Knox. As it was long assumed that the basal Eden in Kentucky was approximately Utica in age the natural upper boundary for Trenton here was the base of the Eden or the top of the Cynthiana. The top of the Cynthiana is difficult to determine even in surface exposure in Kentucky as there is no great faunal or lithologic break.[15] In the subsurface it is even more difficult and that interval is usually referred to as Cynthiana-Million, the Million being the lower part of the Eden. The lower Cynthiana contact with the Lexington limestone below is sharp, however, and can be determined with ease in both surface and subsurface work. Subsurface studies indicate that the Utica shale facies is found progressively lower in the section toward the south, and actually has been identified in the lower 40 feet of the rather persistent 200 feet of Lexington limestone. Thus, considerable confusion exists about the exact stratigraphic interval indicated by the term Trenton. This problem of correlation and lithologic relationships should be studied and an attempt made to understand the exact relations to the Trenton at the type locality.

[15] A. C. McFarlan and Louise B. Freeman, "Rogers Gap and Fulton Formations in Central Kentucky," *Bull. Geol. Soc. America*, Vol. 46, No. 12 (1935), pp. 1975–2006.

LEXINGTON

There was a sharp lithologic change at the close of the Tyrone, with local irregularities at the contact with the overlying Lexington limestone, such as rarely a breccia in the basal Lexington including fragments of Tyrone limestone. The Trenton in Kentucky is said to include the Lexington limestone group and the Cynthiana. During Lexington time in the Cincinnati arch area, local facies changes were so many as to have caused great confusion among early workers and to have resulted in the use of a great many unnecessary names. This problem was explained by McFarlan and White.[16] In spite of the local facies, the Lexington limestone group has enough over-all similarity of lithologic character and interval to make a good mappable unit, either for surface or subsurface work. It can be identified throughout Kentucky and southward into the Hermitage-Cannon of eastern Tennessee, to the Hermitage of western Tennessee, and northward for a short distance into Ohio where it soon loses character by becoming a part of the long sequence of shales known there as Cincinnatian with the Utica at the base.

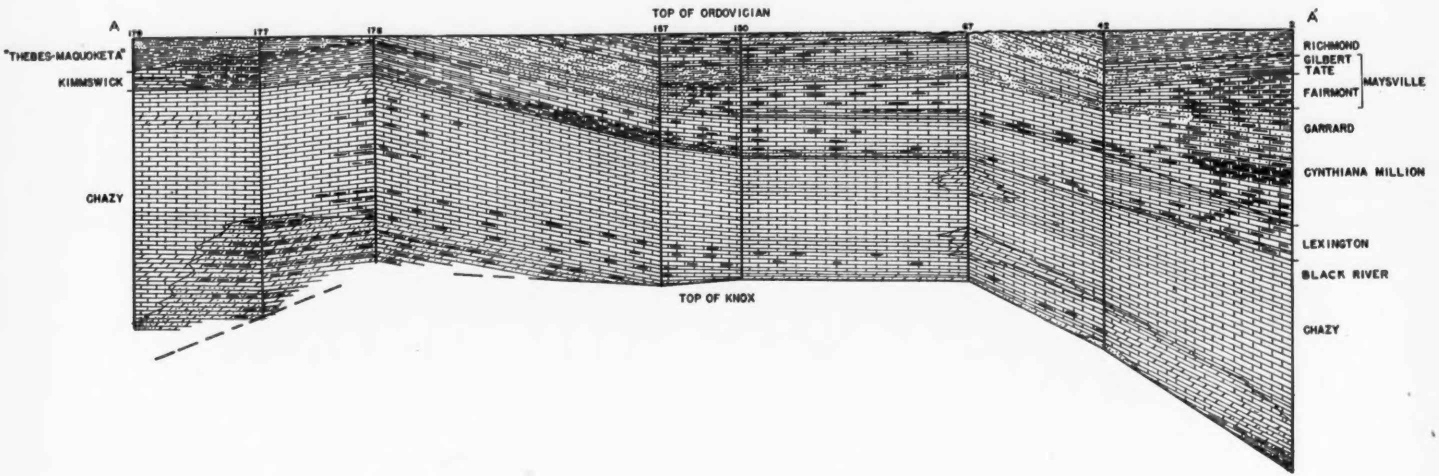
The base of the Lexington is marked by a metabentonite which in northern Tennessee and southern Kentucky is known as the "mud cave." In southern Kentucky the Lexington is mainly brownish gray, fine-grained, argillaceous limestone, lithologically similar to the Cannon of Tennessee, but with a few crystalline, fossiliferous limestone strata like those in central Kentucky. On the south flank of the Lexington dome the top of the Lexington is marked by the first occurrence of the fine-grained, brown limestone, which makes up much of the section on the south and which caused considerable confusion to early stratigraphers—the Salvisa facies.

In tracing the Lexington northward, it is found that the limestone becomes increasingly shaly from the top down, with introduction of a shale of Utica lithology 25–30 feet above the base. Near Cincinnati this Utica-type shale is shown in a well (No. 56), where it is nearly 20 feet thick and the overlying Lexington still has considerable limestone. In Warren County, southern Ohio, the Lexington is still recognizable (well No. 49) as a unit with the Utica-type shale, brown to black, carbonaceous, about 30 feet thick, and occupying a position 30 feet above the base of the Lexington. Farther north, in Logan County (well No. 51), there are 45 feet of Lexington-type limestone below the Utica and the entire section above is slightly calcareous shale which could not be differentiated from the Cincinnatian. Thus, the Utica facies of brown to black shales apparently were being deposited as early as middle Lexington as far south as the Ohio River, and may be time-transgressing, younger northeastward.

While the shales were being deposited through Ohio and northward, limestones, some of them biohermal, with interbedded shales were being formed in northern Kentucky. In southern Kentucky and northern Tennessee slightly argillaceous, fine-grained limestones were formed. The transition from Lexington

[16] A. C. McFarlan and W. H. White, "Trenton and Pre-Trenton of Kentucky," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 8 (August, 1948), pp. 1627–47.

STRATIGRAPHIC SECTIONS OF ORDOVICIAN



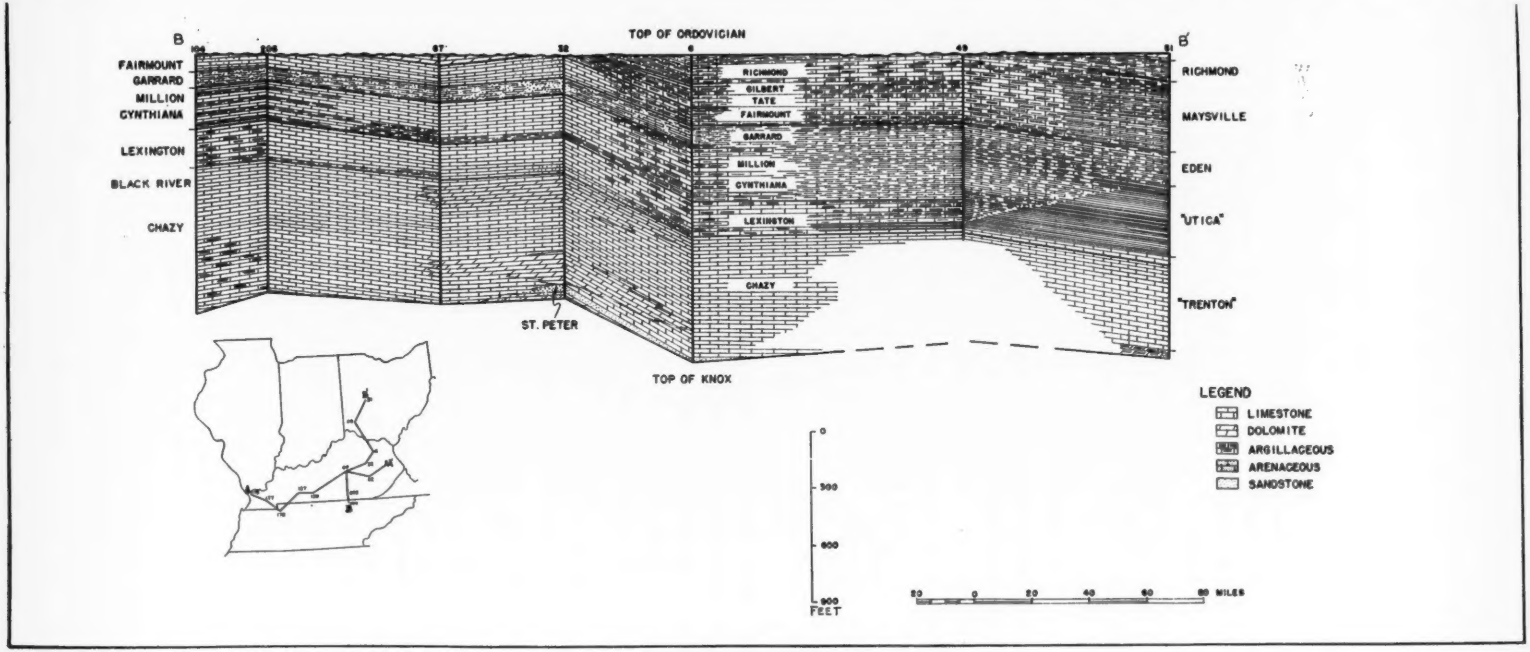


FIG. 6.—Stratigraphic sections of Ordovician.

type lithology to Cannon type occurs in the Cumberland saddle between the Nashville and Lexington domes.

In the direction of the Ozark high the Lexington becomes more shaly and silty (Fig. 6), the silt deposition starting practically at the beginning of Lexington in the Cincinnati arch area and increasing in importance southwestward until the equivalent Hermitage of western Tennessee is essentially shale and silt.

The top of the Lexington limestone is marked by fine, brown limestone with some chert, almost everywhere in the subsurface of Kentucky, that is, both east and west of the Cincinnati arch. The entire section is remarkably uniform in thickness, approximately 200 feet, and the contact with overlying Cynthiana is fairly sharp.

CYNTHIANA

The lower Cynthiana has numerous facies as seen on the outcrop over the Cincinnati arch. These can be recognized in the subsurface. They include the phosphatic Woodburn limestone, the crystalline quarry rock known as the Nicholas with underlying shaly limestone facies, and the interbedded limestones and shales of the Bromley on the north. Later in Cynthiana time the sedimentation became more uniformly fossiliferous, gray, crystalline limestone, slightly phosphatic, with interbedded dark gray, calcareous shales. This type of sedimentation continued into the Eden.

EDEN

The Eden has been subdivided into Fulton, Million, and Garrard in central Kentucky, and Fulton, Economy, Southgate, and McMicken near Cincinnati. It is difficult at the outcrop to recognize the Fulton, thus establishing the contact between Cynthiana and Eden, and it is even more difficult in the subsurface. For that reason the Cynthiana and Million are described together. At the outcrop the Million appears to have more shale than does the underlying Cynthiana, but this characteristic is not discernible in well cuttings. The discrepancy is probably due to weathering phenomena, the shale of the Million being distinctly clayey and the limestone thin-bedded; the clay washes over the surface of the exposure and gives an erroneous impression of the amount of shale. In the cuttings much of the clay is washed out during drilling operations and the excessively thin-bedded character of the limestone can not be determined.

In a small area in Clinton County, Kentucky, there is within the Million a limestone, practically coquina, which possibly represents a biohermal accumulation. The trend of this exceptional limestone is slightly east of north, in general paralleling the present trend of the Cincinnati arch. This is a reservoir for petroleum and is locally known as the "Granville sand." The pattern made by this facies is perhaps 10 miles long and little more than a mile wide. Wells drilled on either side show normal sections of gray, fossiliferous, phosphatic limestone with interbedded calcareous shale. The "Granville" is clean, cream to white, rarely dolomitic, and with rare pink calcite. Beyond the northern end of the productive

area, in Russell County, the limestone is still non-argillaceous but has much red calcite, lithologically similar to the Fernvale of later Ordovician age which may have had a similar origin.

It has been pointed out that the "Granville" limestone seems to underlie the crest of the Illwill anticline.[17] This suggests reef-like accumulation that may have influenced the location and orientation of the anticline. The original depositional dips over it would have created a zone of weakness to subsequent stresses.

The upper Eden in Kentucky is known as the Garrard siltstone. Maysville fossils have been found in the upper part of it in northern Kentucky. This is sandy to silty and argillaceous, dark gray limestone. In the Cincinnati arch area it was long assumed to be rather limited in extent. It is a good horizon-marker because in the subsurface it can be traced not only throughout Kentucky but into Tennessee where it becomes a part of the Hermitage of western Tennessee. It is a time-transgressing silt, starting in Lexington time north of the Ozark upland and extending into the basal Maysville at the Ohio River near Cincinnati. Where there is considerable subsurface control in the vicinity of the Cincinnati arch, it is extremely useful for correlation. Locally the amount and distribution of the silt within the formation varies considerably. In southern Kentucky it is in many places broken by coarsely crystalline limestone with definitely yellow calcite crystals. This limestone may be found overlying the silt, within it, or may be split into two limestone breaks in the silt. This particular character seems to be limited to the southern and southeastern flanks of the Lexington dome.

The stratigraphic section (Fig. 6) from Ballard County, Kentucky, in the Mississippi embayment, across the south flank of the Lexington dome into eastern Kentucky, suggests that the black silt and shale which are known as Thebes-Maquoketa in the embayment actually are considerably older. Possibly the silt accumulation began there soon after deposition of Kimmswick (Trenton) and more nearly approaches time equivalency with the Cynthiana-Eden in central Kentucky than with the Richmond. The source of the Garrard silts then was the lowland area of the southeastern extension of the Ozark upland.

MAYSVILLE

The Fairmount, lower member of the Maysville, is a series of limestones, very fossiliferous and phosphatic, with interbedded calcareous shale, similar, excepting for faunal content, to the underlying Cynthiana-Million. In southern Kentucky it is an easily mappable unit about 120 feet thick, having sharp lithologic contact with the underlying Garrard silt and with the overlying Tate green dolomitic siltstone. The Garrard facies rises in the section northward, at the expense of Fairmount. The Tate loses silt northward, becoming increasingly calcareous, argillaceous, and gray. Just as the Lexington limestone becomes increasingly shaly northward, so do the other members easily recognizable in Kentucky, until the entire section above the lower 20–30 feet of Lexington is

[17] Woodson Diamond, *The Desda Oil Pool*, private publication (1943).

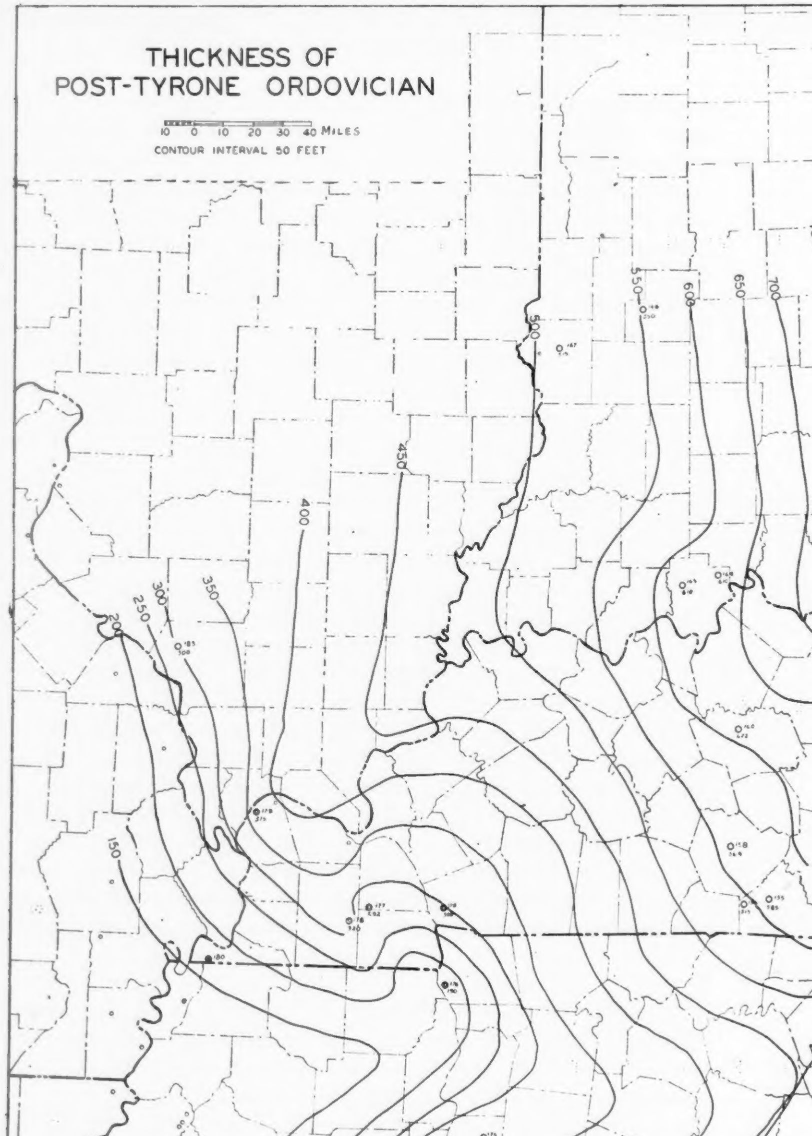
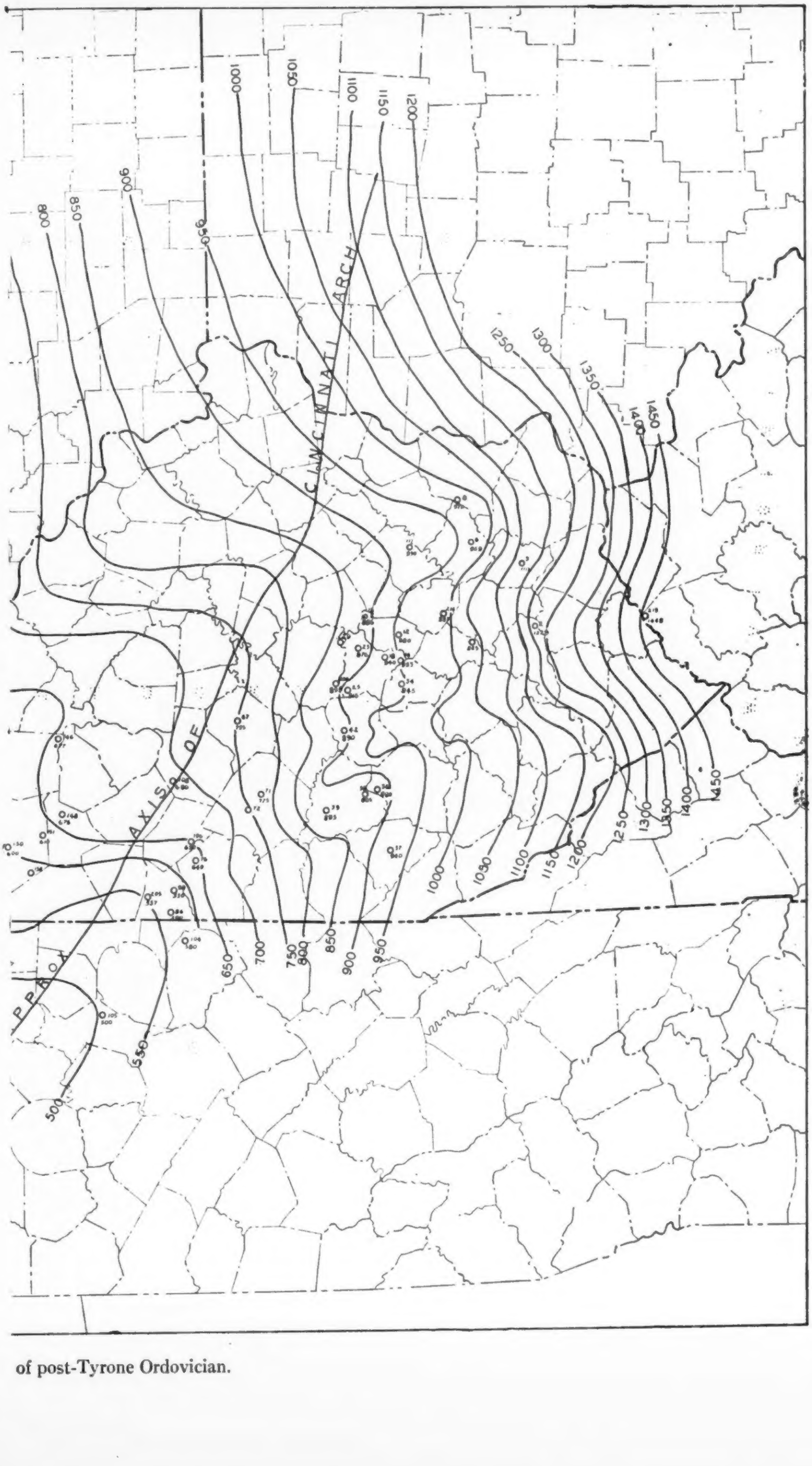


FIG. 7.—Map showing thickness



of post-Tyrone Ordovician.

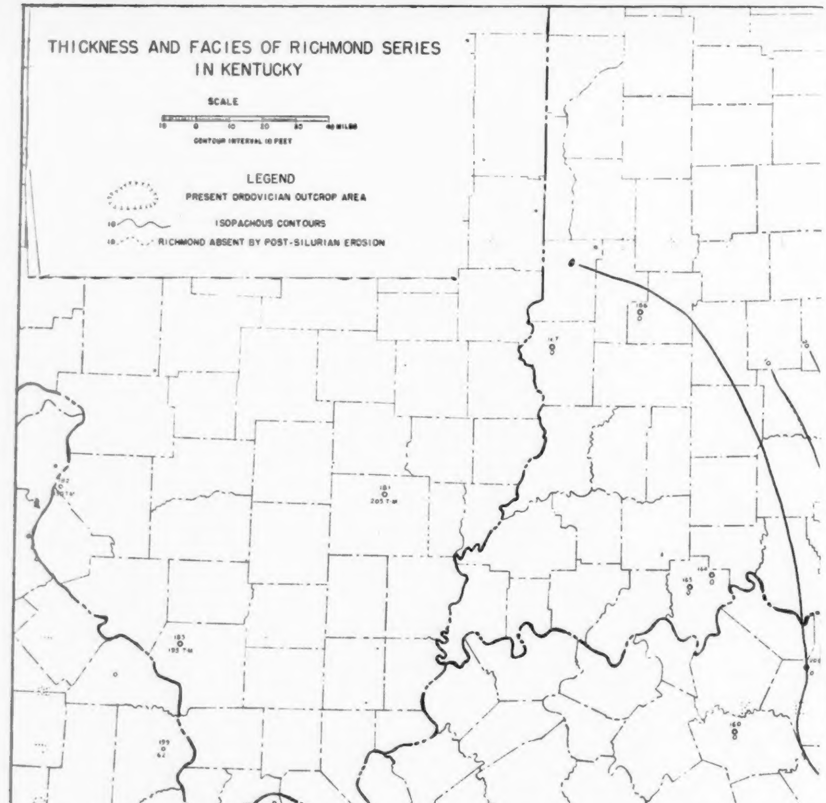
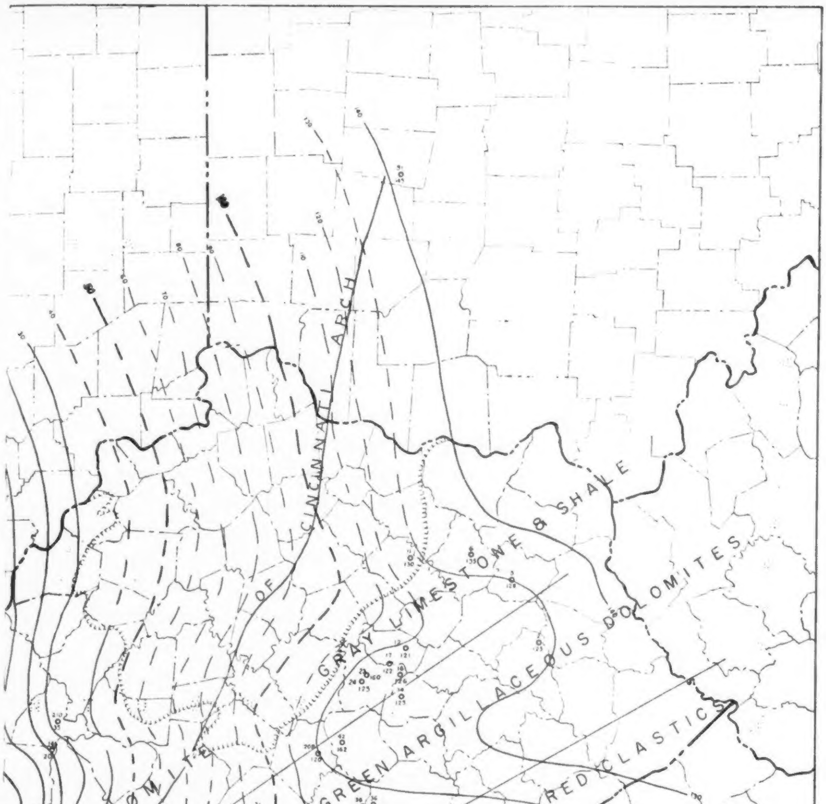


FIG. 8.—Map showing thickness



and facies of Richmond.

occupied by undifferentiated Cincinnatian calcareous shale in Ohio and Indiana. This is also true east of the Cincinnati arch in Kentucky, where these units are gradually lost in the Martinsburg shale.

A new source for clastics became available near the end of Maysville time, however. Silts from this new eastern source, which was to affect the Richmond in the southern Appalachians, reached southern Kentucky and Tennessee during the later part of Maysville time, forming the Tate formation. It may be that the lower part of the Red Medina, or Queenston, is equivalent to the Tate of central Kentucky. Again the question arises where to draw the contact between the two groups, the Richmond and Maysville, when the new source suggests a major break at the base of the Tate, while on the north and east continuous deposition of marine-type gray limestones and shales characterizes these formations.

There is a limestone break, the Gilbert, which makes it possible to determine the top of the Maysville on the subsurface in Kentucky. This is thin, heavy-bedded, almost black limestone, very fine-grained and dense. In few places it is more than 8–10 feet thick. Since the entire Richmond northward becomes increasingly calcareous, argillaceous and non-silty, the Gilbert may be the first of such limestone facies to appear. The Tate silt is so similar to the Richmond and is essentially so barren of fossils that it has been commonly mistaken for Richmond at the outcrop. For instance, the so-called Saluda of the outcrop area on the west side of the Cincinnati arch in Kentucky is commonly Tate, and what has been called Richmond in south-central Kentucky is almost everywhere Tate.

RICHMOND

The close subsurface control which is available shows that the Richmond thins westward (Fig. 8) and is completely absent in many places before it crops out on the west flank of the arch. A thickness map of the Richmond indicates that the Ozarks-extended must have been high during this time and Richmond was either not deposited or was later eroded. The distribution of the post-Kimmswick silts and shales of the Mississippi Valley, and the Richmond channel fills in southern Tennessee, described recently by Wilson,[18] tend to confirm this theory.

The isopachous map (Fig. 8) of the Richmond indicates that it thins to extinction slightly west of the present Cincinnati arch in Kentucky, and without regard to the arch. The zero line can be drawn with fair accuracy. The dashed lines indicate the area where the Richmond is absent through post-Silurian erosion over the arch. In that area the Maysville is overlain by either a remnant of Middle Devonian limestone, or by the Chattanooga black shale. Throughout the rest of the area of known occurrence the Richmond is overlain by Brassfield, basal Silurian, in normal sequence.

One of the problems created by this study is: what part of the strata mapped as Thebes-Maquoketa in the Illinois basin is actually equivalent to the Cyn-

[18] C. W. Wilson, Jr., "Channels and Channel-Filling Sediments of Richmond Age in South Central Tennessee," *Bull. Geol. Soc. America*, Vol. 59, No. 8 (August, 1948), pp. 733–66.

thiana-Eden in Kentucky, and what part is the southwestward extension of Richmond deposition toward the Ozarks. Richmond was not identified in wells in Perry County, or in Sullivan County, Indiana.

Another problem is the Fernvale which occurs through a small area in northwestern Tennessee and adjoining Kentucky as a crystalline limestone with much pink calcite, but containing *Rhynchotrema capax*. It is only 20–30 feet thick and directly underlies the Brassfield and overlies the Hermitage. W. H. Shideler[19] said that in many respects the Fernvale of Tennessee is different from that in the western Ozarks. Perhaps re-examination might prove it slightly older.

Near the southern part of the Lexington dome, the Richmond is mainly green, argillaceous, silty dolomite. Northeastward it becomes first more calcareous, then less green and silty, until just south of the Ohio River it is lithologically similar to the underlying Maysville, that is, fossiliferous gray limestone with interbedded calcareous shale, the shale increasing northward. In a small area on the west, the Richmond is very dolomitic, having here and there clean but thin dolomites which have contained a little oil.

On the southeast the Richmond becomes increasingly silty, with the green color changing to red, first as red silty shales, then red silts, and finally the red sandstones of the Medina.

For a short period following deposition of the Richmond, all land areas on the west were low, and the waters shallow and ideal for the formation of widespread but thin limestone, the Brassfield. Clastic sedimentation continued in the Appalachian basin on the east, the Red Medina clastics being followed by white sands, but from eastern Kentucky westward through all of the area affected by the Cincinnati arch and the Ozarks, there was a great lull. Following this, for the first time, the Cincinnati arch had appreciable effect on sedimentation. At first it acted as a barrier to the clays being washed into the Silurian seas from the east, and later in the Silurian it was high enough to contribute sediments to early Devonian deposition.

[19] W. H. Shideler, department of geology, Miami University; personal communication.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1682-1703, 8 FIGS.

SUBSURFACE UPPER DEVONIAN SECTIONS IN SOUTHWESTERN PENNSYLVANIA[1]

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ABSTRACT

With the exception of small inlier areas along the axes of Chestnut Ridge and Laurel Ridge anticlines, the Upper Devonian rocks of western and southwestern Pennsylvania are concealed beneath a mantle of overlying Mississippian, Pennsylvanian, and Permian sediments. Thus, the study of this very important group of rocks becomes a problem for the subsurface stratigrapher in approximately half of the surface area of Pennsylvania. Drilling, in recent years, along Chestnut Ridge and Laurel Ridge anticlines and also in the broad plateau area between Laurel Ridge and the Allegheny Front has yielded many excellent sections based on detailed examinations of drill cuttings. Some of these sections, in a generalized graphic form, together with additional sections in the oil- and gas-producing area west of Chestnut Ridge, are assembled into cross sections which illustrate the facies variations in the Upper Devonian sediments of southwestern Pennsylvania. The Conewango (uppermost Upper Devonian) age of the Devonian rocks exposed in the inlier areas of Chestnut Ridge and Laurel Ridge anticlines is confirmed. With the exception of the Huntersville chert and Oriskany sandstone, which are Lower Devonian in age, the producing sands of southwestern Pennsylvania all appear to be younger than the highest sub-Catskill marine beds exposed along the Allegheny Front, which are generally considered as being late Chemung in age.

INTRODUCTION

With the exception of small inlier areas along the axes of Chestnut Ridge and Laurel Ridge anticlines, the Upper Devonian rocks of western and southwestern Pennsylvania are concealed beneath a mantle of overlying Mississippian, Pennsylvanian, and Permian sediments. Thus, the study of this very important group of rocks becomes a problem for the subsurface stratigrapher in approximately half of the surface area of Pennsylvania. Fortunately, nearly all of the oil and more than 50 per cent of the gas produced in Pennsylvania are derived from rocks of this age, so that several hundred sets of drill cuttings, supplemented by thousands of driller's logs are available to the geologist. The present paper is an attempt to continue underground, through detailed studies of drill cuttings, the correlation of the upper part of the Devonian section, as exposed along the Allegheny Front, tying in with the exposed inlier sections of Fayette and Westmoreland counties and continuing across the present producing fields of the southwestern part of the state.

FACIES DEVELOPMENT

The seas which occupied the interior of the North American continent during Upper Devonian time included a broad embayment which extended across much

[1] Read before the Association at Pittsburgh, October 5, 1948. Manuscript received, March 11, 1949. Published by permission of The Peoples Natural Gas Company.

[2] Geologist, The Peoples Natural Gas Company. The writer wishes to acknowledge the encouragement and support of F. H. Finn, chief geologist for The Peoples Natural Gas Company. It is probable that in any paper of this sort the ideas and suggestions of many geologists are incorporated. However, it would be impossible to acknowledge each individually, and so to all those friends and associates, but especially to J. H. C. Martens and C. R. Fettke, who have contributed so generously of their time and suggestions during the past 10 years, grateful acknowledgment is hereby made. Special thanks, also, are due Ray Morwood, cartographer, whose excellent drawings add immeasurably to the value of this paper.

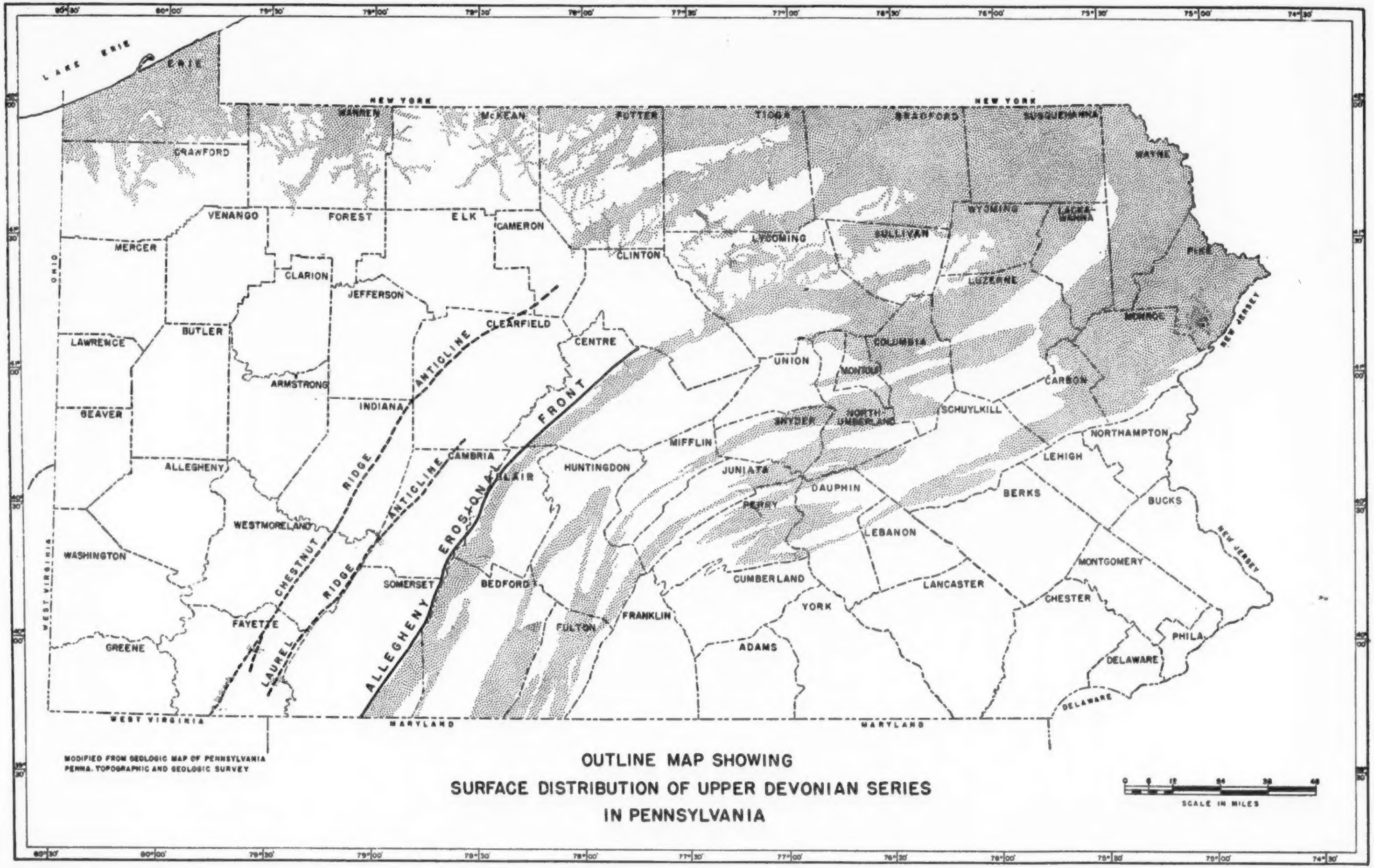

OUTLINE MAP SHOWING
SURFACE DISTRIBUTION OF UPPER DEVONIAN SERIES
IN PENNSYLVANIA
MODIFIED FROM GEOLOGIC MAP OF PENNSYLVANIA
PENNA. TOPOGRAPHIC AND GEOLOGIC SURVEY
SCALE IN MILES
LAKE ERIE
NEW YORK
NEW JERSEY
MARYLAND
WEST VIRGINIA
OHIO
DELAWARE
ALLEGHENY EROSIONAL FRONT
CHESTNUT RIDGE
LAUREL RIDGE
ANTICLINE
ANTICLINE
ERIE
CRAWFORD
WARREN
McKEAN
POTTER
TIOGA
BRADFORD
SUSQUEHANNA
WAYNE
VENANGO
FOREST
ELK
CAMERON
CLINTON
LYCOMING
SULLIVAN
WYOMING
LACKAWANNA
LUZERNE
PIKE
MONROE
MERCER
CLARION
JEFFERSON
CLEARFIELD
CENTRE
UNION
MONTOUR
COLUMBIA
CARBON
LAWRENCE
BUTLER
ARMSTRONG
INDIANA
SNYDER
NORTHUMBERLAND
SCHUYLKILL
NORTHAMPTON
BEAVER
ALLEGHENY
CAMBRIA
BLAIR
HUNTINGDON
MIFFLIN
JUNIATA
DAUPHIN
LEHIGH
BERKS
BUCKS
WESTMORELAND
PERRY
LEBANON
WASHINGTON
SOMERSET
BEDFORD
CUMBERLAND
LANCASTER
MONTGOMERY
CHESTER
YORK
FAYETTE
FULTON
FRANKLIN
GREENE
ADAMS
PHILA
DELAWARE

FIG. 1

of what is now Pennsylvania and southern New York.[3] Into this embayment, termed the "Penn-York embayment" by Caster, sediments were deposited which to-day comprise the shales, siltstones, and sandstones of the Upper Devonian series. These sediments were deposited during the regressive or offlap stage of a great sedimentary cycle and, as such, exhibit all the characteristics of rocks formed under those conditions. The eastern border of this embayment in Middle Devonian time (early Hamilton) was in the approximate position of the present Catskill Mountains and northern New Jersey. This marks its maximum flood and as the highlands on the east and southeast were elevated, the closing or offlap stage of the cycle began.

The westward-flowing streams spread fan-like over a gently sloping coastal plain, depositing huge quantities of detrital material along their flood plains and on ever widening coalescing deltas. With the passage of late Devonian time, the continental facies encroached westward covering previously deposited marine sediments. As this progressive shift occurred, the offshore marine facieological belts also shifted westward, grading into one another horizontally and vertically, and each containing its characteristic fauna, but becoming ever younger. Though any particular facies belt, continental or marine, would be mapped as a lithologic unit, the time of its deposition constantly changed and at no two points in the direction of regression would it be precisely the same in age. Caster has called these ever widening facieological belts which transcend time lines "magnafacies" —a very useful term.

STRATIGRAPHY

Because of the facieological character of the Devonian rocks of Pennsylvania, it is impossible to present a single table applicable to the state as a whole in which all recognized units are listed. However, the following somewhat generalized table, taken from Willard's report on the Devonian of Pennsylvania,[4] illustrates the presently accepted chronologic relationship of one major subdivision with another.

Although Willard did not so state, it is apparent from the text of his report that he uses the word "group" in the sense recommended by the committee representing the American geological societies in 1933[5] and so is equivalent to the "stage" of international usage. Although it is both desirable and necessary that

[3] Kenneth E. Caster, "The Stratigraphy and Paleontology of Northwestern Pennsylvania, Part I, Stratigraphy," *Bulletins Amer. Paleon.*, Vol. 21 (1934), pp. 20–21.
Bradford Willard, "The Devonian of Pennsylvania," *Pennsylvania Geol. Survey Bull. G19*, 4th Ser. (1939), pp. 362–79.
Wilson M. Laird, "The Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 126* (1941), p. 4.
———, "The Stratigraphy of the Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *unpublished doctorate thesis, Univ. Cincinnati* (1942), pp. 12–20.

[4] Bradford Willard, *op. cit.*, p. 12.

[5] "Classification and Nomenclature of Rock Units," by G. H. Ashley *et al.*, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 7 (July, 1933), pp. 843–63.

- Upper Devonian
  - Conewango group
  - Conneaut group
  - Canadaway group
  - Chemung group
    - Wellsburg formation
    - Cayuta formation
  - Portage group
    - Fort Littleton formation
      - Brallier shale—Trimmers Rock sandstone
      - Losh Run shale
      - Harrell shale
    - Rush formation
      - Burket shale
      - Tully limestone
- Middle Devonian
  - Hamilton group
  - Onondaga group
- Lower Devonian
  - Oriskany group
  - Helderberg group

Catskill continental facies equivalent in northeastern Pennsylvania

some subdivision based on time be attempted, nevertheless, the time value of many of these units is questionable. As an example, without regard to the fact that several separate and distinct species, subspecies, and mutants are all called "*Spirifer*" *disjunctus*, the base of the Chemung is everywhere drawn on the first appearance of this "distinctive" brachiopod. However, when one considers the facieological character of these beds, it is readily apparent that the first appearance of a fossil may occur on the east at a much earlier date. As the environmental belt in which a particular species may flourish shifts westward, and upward, ahead of the advancing shoreline, so also will the first appearance of the species shift westward and upward. Caster has rather minutely subdivided the upper part of the Upper Devonian section exposed in northwestern Pennsylvania and southern New York,[6] but it seems likely that this, as well as other subdivisions now in use, will be subject to revision in the future should these rocks, with their enclosed faunas, ever be studied in the detail necessary to establish their precise relationships.

CENTRAL AND EASTERN PENNSYLVANIA: SURFACE STRATIGRAPHY

As pointed out by Willard in his report on "The Devonian of Pennsylvania,"[7] a horizontal and vertical lithologic gradation characterizes the exposures of the Upper Devonian rocks in central and eastern Pennsylvania. Along the Allegheny Front the black, fissile, calcareous Burket shale grades upward into the dark gray Harrell shale, which in turn grades imperceptibly into the overlying gray to greenish gray Brallier shale. Thin interbeds of greenish gray siltstone appear in the upper part of the Brallier, and as these become more numerous, the Brallier passes into the interbedded greenish gray shales and siltstones of the Chemung, containing lenticular sandstone and conglomerate beds here and there. Thus,

[6] Kenneth E. Caster, *op. cit.*, pp. 61–102.

[7] Bradford Willard, *op. cit.*, pp. 201–307.

there is constant, vertical gradation from the black calcareous shales of the Burket to the greenish gray interbedded shales, siltstones, and sandstones of the Chemung. No sharp line of lithologic differentiation can be drawn in this sequence of strata which is approximately 5,000 feet thick along the Allegheny Front.

The same relationship prevails horizontally eastward. Along the lower Juniata and Susquehanna valleys the Trimmers Rock sandstone, which is considered a near-shore equivalent of the Brallier, is identical, lithologically, with the Chemung of the Allegheny Front. Farther east, this sandy facies moves downward in the section resting on older and older beds. Basal Brallier and Losh Run shales first grade into the sandy facies, then the Harrell, followed by the Burket, so that in Monroe County in the eastern part of the state the Chemung-Trimmers Rock type of sediments rests directly on lithologically similar upper Hamilton beds, and differentiation is based solely on doubtful faunal evidence.

Overlying these marine beds are the redbeds of continental origin, here referred to as the Catskill continental magnafacies. Along the Allegheny Front at Altoona the continental redbeds rest on and interfinger with marine beds containing an upper Chemung (Wellsburg) fauna.[8] Along the Delaware River the base of the Catskill rests on the Trimmers Rock sandstone, which in this area, according to Willard, is middle Portage or somewhat younger. Farther east and northeast in New Jersey and New York the base of the Catskill rests on marine beds of early Hamilton age.

It is evident, therefore, that the Upper Devonian sequence in Pennsylvania is a classic example of the facies relationships of sediments deposited before an advancing shoreline. Caster, Chadwick, Laird, Willard, and others have emphasized the facieological character of these beds in their more recent publications, and while much has been accomplished, much more remains to complete the understanding of these Upper Devonian rocks.

SOUTHWESTERN PENNSYLVANIA: SUBSURFACE STRATIGRAPHY

A discussion of the Upper Devonian rocks of western and southwestern Pennsylvania evolves into two separate discussions. The first has to do with the subsurface correlations of the area, and here, although the literature is perhaps not as comprehensive and voluminous as desired, there is surprisingly little disagreement. There are certain correlations, most of which have appeared in print and others which are a part of the common knowledge of the oil and gas geologists working in the area, that have gained general acceptance.

The first consideration in correlating the subsurface Upper Devonian rocks in southwestern Pennsylvania is the location of that hypothetical plane which marks the base of the Mississippian and the top of the Devonian. This is, of course, subject to interpretation by the surface stratigrapher in his studies of the exposures of these rocks elsewhere in Pennsylvania and its neighboring states. Through the years this boundary has been moved up and down through several hundred feet

[8] Bradford Willard, *op. cit.*, pp. 261–68.

of section, but as interpreted at the present time by Caster, Cathcart, Laird, Willard, and other leading stratigraphers of the area, it is drawn at the base of the Knapp group as it is developed in McKean County, Pennsylvania. Chadwick,[9] in 1925, called attention to the lithological similarity of the Cussewago sandstone of Ohio and the Knapp conglomerate of northwestern Pennsylvania and concluded that the Cussewago shale, renamed Hayfield, and the Cussewago sandstone are equivalent to the Knapp group in age. Caster, in 1933,[10] and again in 1934,[11] substantiated this correlation and placed the base of the Mississippian at the base of the Knapp.

The correlation of the Murrysville producing sand of southwestern Pennsylvania with the Knapp appears to be well substantiated. Laird, in 1941,[12] and again in 1942,[13] on the basis of faunal evidence, correlated certain beds exposed in the inlier areas of southwestern Pennsylvania as Knapp. Closely spaced well sections, based on detailed studies of drill cuttings, establish these beds as being the equivalent of the Murrysville sand as it is developed in Westmoreland County. In 1946, Demarest,[14] again through closely spaced well records, correlated the Murrysville sand with the Cussewago sandstone of Ohio. Thus, the correlation of the Murrysville sand with the Cussewago sandstone and the Knapp conglomerate is established and in southwestern Pennsylvania the base of the Mississippian is drawn at or near the base of the Murrysville sand. In sections based on studies of drill cuttings, the base is actually drawn at the point below the Murrysville where the rocks show the characteristic greenish gray color of the Devonian sediments. In many places, therefore, a gray shale varying in thickness from a few inches to 30 feet occurs below the Murrysville and is included in the Mississippian. It is possible that this shale corresponds with the Kushequa shale of Caster.[15]

The Conewango group of northwestern Pennsylvania has been subdivided into the Riceville and the underlying Venango formations. The Riceville is the exact equivalent of the Oswayo formation of McKean County, and the marine Venango appears to be equivalent to the continental Cattaraugus formation of McKean

[9] George H. Chadwick, "Chagrin Formation of Ohio," *Bull. Geol. Soc. America*, Vol. 36 (1925), p. 463.

[10] Kenneth E. Caster, "Stratigraphic Relationships in Northwestern Pennsylvania" (abstract), *Bull. Geol. Soc. America*, Vol. 44 (1933), pp. 202–03.

[11] *Idem*, "The Stratigraphy and Paleontology of Northwestern Pennsylvania, Part I, Stratigraphy," *Bulletins Amer. Paleon.*, Vol. 21 (1934), pp. 104–06.

[12] Wilson M. Laird, "The Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 126* (1941), pp. 5 and 12.

[13] *Idem*, "The Stratigraphy of the Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *unpublished doctorate thesis, Univ. Cincinnati* (1942), pp. 12–20.

[14] David F. Demarest, "The Berea and Murrysville Sands of Northwestern Ohio, Western Pennsylvania and Northernmost West Virginia," *U. S. Geol. Survey Prelim. Map 49*, Oil and Gas Investig. Ser. (1946).

[15] Kenneth E. Caster, *op. cit.* (1934), pp. 103–05.

County.[16] In the subsurface sections of southwestern Pennsylvania, the top of the Conewango is placed at or near the base of the Murrysville sand, as has been indicated, and the bottom is drawn at the top of the Fifth Bayard sand group.

As so defined, the Conewango group includes the Catskill continental magnafacies as it is developed in that part of southwestern Pennsylvania which lies west of Laurel Ridge. The bottom, placed here at the base of the Catskill redbeds, is not an exact plane of contemporaneity, being somewhat younger on the west. However, for practical purposes in subsurface stratigraphy, it is quite satisfactory.

Many attempts have been made to correlate the individual producing sands of the Conewango group in southwestern Pennsylvania with their surface equivalents in the northwestern part of the state. However, when one considers the lenticular nature of these sand bodies and the fact that at the time the efforts were made the only well records available were drillers' logs, these correlations can not be accepted as final. The Gantz and Fifty-Foot sands of Greene, Fayette, and Washington counties in the extreme southwestern corner of Pennsylvania, where traced northeastward, are found to merge into a single sand body known as the Hundred-Foot sand. Continuing north and northeastward, the Hundred-Foot sand is correlated with the First Sand formation of the Venango district, which in turn is believed to occupy approximately the same stratigraphic position as the Woodcock sandstone of Crawford County and the Tuna-Killbuck conglomerate of McKean County,[17] both of which occur at or near the top of the Venango formation as defined by Caster. Here an apparent discrepancy exists. Eastward, the Hundred-Foot sand grades into a shaly sequence which has been correlated as Oswayo by Fettke and the writer in their work in the Conemaugh Gorge near Johnstown, Pennsylvania, in 1945.[18] In 1941, Wilson Laird, in his carefully measured section through the Youghiogheny Gorge near Ohiopyle, Pennsylvania, tentatively correlated a sandstone exposed there with the Riceville of northwestern Pennsylvania.[19] Later studies indicate that this sandstone is the Hundred-Foot sand of the subsurface sections. It is apparent, therefore, that much more detailed work must be done before individual Upper Devonian subsurface sand bodies can be correlated with their surface equivalents in northwestern Pennsylvania—if ever they can be.

The Gordon Stray producing sand of southwestern Pennsylvania, traced north and northeastward, is correlated with the Second Sand formation of the

[16] *Ibid.*, pp. 54–60.

[17] *Ibid.*, pp. 92–93.
Charles R. Fettke, "The Bradford Oil Field," *Pennsylvania Geol. Survey Bull. M21*, 4th Ser. (1938), pp. 34–35.

[18] Charles R. Fettke and Robert E. Bayles, "Conemaugh Gorge Section of the Mississippian System Southeast of Cramer, Pennsylvania," *Proc. Pennsylvania Acad. Sci.*, Vol. 19 (1945), pp. 93–94.

[19] Wilson M. Laird, "The Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 126* (1941), pp. 11–12.

Venango district, which in turn has been correlated with the Salamanca conglomerate of Warren and McKean counties.[20]

In a like manner, the Gordon and Fourth sands of southwestern Pennsylvania may be correlated with the Third Sand formation of the Venango district. The Third Sand formation has been correlated with the Panama-Wolf Creek conglomerates at the base of the Venango formation where it crops out in northwestern Pennsylvania.[21] Fettke and Stevenson, in their recent report on the "Oil and Gas Developments in the North Strabane Area, Washington County,"[22] include the Fifth Sand with the Gordon and Fourth sands as being equivalent to the Third Sand formation of the Venango district. However, in many subsurface sections in southwestern Pennsylvania, it is impossible to separate the Fifth Sand from the underlying Bayard and Bayard Stray sands, and, as these members are generally included in the Conneaut group, it seems desirable and convenient for the Fifth Sand to be included in the Conneaut as well.

A detailed study of the section below the Conewango group in southwestern Pennsylvania for the purpose of correlating these rocks with their surface and subsurface equivalents in Warren and McKean counties has yet to be made. Therefore, only general statements are possible at this time about their position in the northwestern Pennsylvania section.

The Conneaut group of southwestern Pennsylvania consists predominantly of interbedded gray to greenish gray marine shales and siltstones, with the lenticular sandstones and conglomerates of the Fifth Bayard sand group occurring at the top. In many sections, but not all, the upper part of the Conneaut has a grayish red or purplish gray hue and is referred to as the "pink rock" by drillers. The base of the Conneaut in southwestern Pennsylvania can not be drawn at present, but it probably occurs at or near the Speechley sand horizon, with the Speechley sand belonging in the underlying Canadaway group.

As defined in southwestern New York, the top of the Canadaway group is placed at the base of the Cuba sandstone and the bottom at the base of the Dunkirk shale. Fettke, in his report on the Bradford oil field, has correlated the Cuba sandstone with the Bradford 1st sand and placed the base of the Dunkirk shale 700–900 feet below the Bradford 3d sand.[23] In the absence of detailed studies over the intervening area, it is impossible to locate these boundaries in the subsurface sections of southwestern Pennsylvania. However, it is probable that the rocks between the Speechley sand and the 3d Bradford sand, inclusive,

[20] Kenneth E. Caster, *op. cit.* (1934), pp. 85–89.
Charles R. Fettke, *op. cit.* (1938), pp. 34–35.

[21] Kenneth E. Caster, *op. cit.* (1934), pp. 77–83.
Charles R. Fettke, *op. cit.* (1938), pp. 34–35.

[22] Charles R. Fettke, Robert C. Stevenson, and E. M. Tignor, "Oil and Gas Developments in the North Strabane Area, Washington County, Pennsylvania," *Pennsylvania Geol. Survey Bull. M28*, 4th Ser. (1946), pp. 22–23.

[23] Charles R. Fettke, *op. cit.* (1938), pp. 145–48.

belong to the Canadaway, with the possibility that the bottom of the group may occur several hundred feet lower in the section. Sisler, in 1930, pointed out that the Bradford 3d sand of the Bradford area and the 3d Bradford sand of southwestern Pennsylvania occupy approximately the same stratigraphic position.[24]

With the exception of the Tully-Burket contact, further subdivision of the Upper Devonian sequence in southwestern Pennsylvania is now impossible. The same vertical gradation of sediments which prevails east of the Allegheny Front also occurs in the subsurface sections.[25]

SOUTHWESTERN PENNSYLVANIA: SURFACE STRATIGRAPHY

A discussion of the Upper Devonian subsurface stratigraphy of southwestern Pennsylvania would not be complete without some reference to the exposures of these rocks in the inlier areas along Chestnut Ridge and Laurel Ridge anticlines and a brief review of the controversy about them which has continued for many years.[26]

J. J. Stevenson, in 1878,[27] first proposed the idea of a hiatus in this area by which a large part of the Upper Devonian section was removed. He based this belief on the identification of certain fossils as "lower Chemung" in age which he found in the uppermost Devonian. Although Stevenson himself partly repudiated his earlier belief in 1903,[28] he was, nevertheless, supported in it in 1902 by M. R. Campbell[29] when he stated that the highest Devonian rocks of the area were "Chemung" in age and that no formation intervened between them and the Lower Mississippian strata.

Charles Butts, in 1908,[30] differed with the earlier work of Stevenson and Campbell, concluding from faunal evidence that the uppermost Devonian rocks

[24] James D. Sisler *et al.*, "Contributions to Oil and Gas Geology of Western Pennsylvania," *Pennsylvania Geol. Survey Bull. M19*, 4th Ser. (1933), pp. 28.

[25] For more detailed descriptions of Upper Devonian lithology the reader is referred to the following.

C. R. Fettke, "Subsurface Devonian and Silurian Sections across Northern Pennsylvania and Southern New York," *Bull. Geol. Soc. America*, Vol. 44 (1933).

———, "Subsurface Sections across Western Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 127* (1941).

P. A. Dickey, R. E. Sherrill, and L. S. Matteson, "Oil and Gas Geology of the Oil City Quadrangle," *ibid.*, *Bull. M25*, 4th Ser. (1943).

J. H. C. Martens, "Petrography and Correlation of Deep-Well Sections in West Virginia and Adjacent States," *West Virginia Geol. Survey*, Vol. 11 (1939).

———, "Well Sample Records," *ibid.*, Vol. 17 (1945).

[26] Wilson M. Laird, "The Stratigraphy of the Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *unpublished doctorate thesis, Univ. Cincinnati* (1942), pp. 23–34.

[27] J. J. Stevenson, "The Upper Devonian Rocks of Southwestern Pennsylvania," *Amer. Jour. Sci.*, 3d Ser., Vol. 15 (1878), pp. 423–30.

[28] *Idem*, "Lower Carboniferous of the Appalachian Basin," *Bull. Geol. Soc. America*, Vol. 14 (1903), pp. 15–96.

[29] M. R. Campbell, "Masontown-Uniontown, Pennsylvania," *U. S. Geol. Survey Geol. Atlas Folio 82* (1902), p. 6.

[30] Charles Butts, "Pre-Pennsylvanian Stratigraphy," *Rept. Pennsylvania Topog. and Geol. Survey, 1906–1908* (1908), pp. 190–204.

of the inlier area were equivalent to the Conewango group of northwestern Pennsylvania. Butts was not clear in his own mind, however, whether the Conewango was Devonian or Mississippian or should bridge the two.

The controversy rested here for many years until Willard, in 1933,[31] reopened the discussion by virtually restating Stevenson's early contention that a large unconformity exists between the Mississippian and Devonian strata in southwestern Pennsylvania. Willard considered the Devonian strata of the inliers to be equivalent to the Cayuta formation (lower Chemung) of New York. By inference, therefore, the Wellsburg formation (upper Chemung), the Canadaway, Conneaut, and Conewango groups were supposedly absent in southwestern Pennsylvania.

In 1935, Chadwick,[32] on the basis of literature surveys and personal examination of the area, concluded that the rocks in question were Canadaway in age. Thus, he too implied a large hiatus.

Caster, in a discussion with Willard in 1935,[33] concurred with Butts and expressed his belief that the strata in question were Conewango in age, basing his decision on his identification of several diagnostic fossils which have never been determinatively reported outside the Conewango.

Willard, in his report on the Devonian of Pennsylvania in 1939,[34] places considerable emphasis upon the supposed absence of the Catskill redbeds as a support for his belief regarding the early Chemung age of these rocks. Referring to the Devonian strata found on Chestnut Ridge, he states that the "Fossiliferous beds are capped by pebbly strata assigned to the Pocono with no Catskill redbeds between." This is quite true. The Catskill redbeds are not exposed at the surface and occur 200 feet or more below the fossiliferous beds in question. Ample proof of this lies in the many well sections now available in the vicinity of these outcrops. Willard states further that in the Conemaugh Gorge west of Johnstown "the Pocono overlies marine Devonian beds without intervening red strata." This is also true. The red strata occur 200 feet below the marine Devonian beds referred to, but here they are exposed. Proof of this is offered in the form of a measured section compiled by Fettke and the writer in 1945.[35] Willard shows signs of uncertainty, however, when he states that the "Fossils on Chestnut Ridge are probably of late Chemung age, but may be younger."

The most recent and authoritative study of the area was completed in 1942 by Wilson M. Laird as a partial fulfillment of the requirements for the Doctor

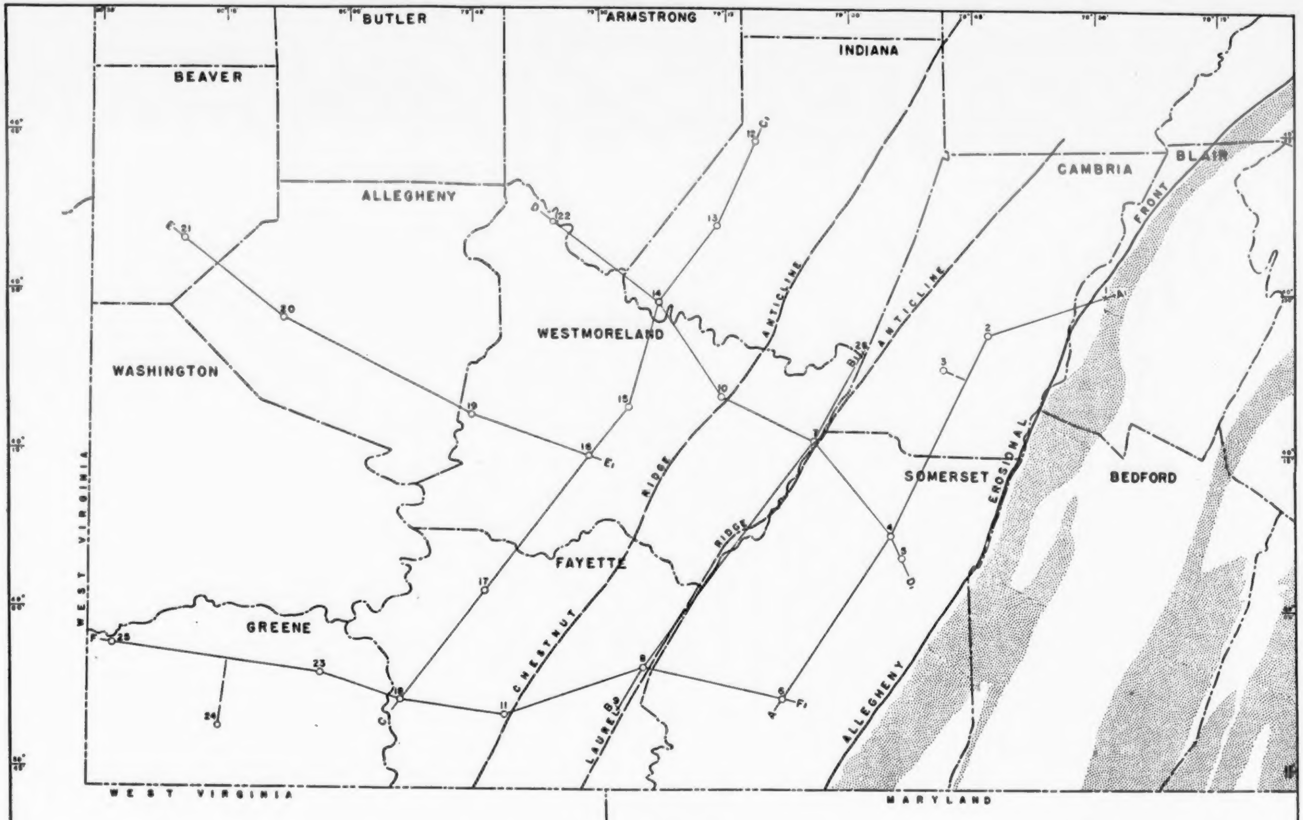
[31] Bradford Willard, "Chemung of Southwestern Pennsylvania," *Proc. Pennsylvania Acad. Sci.*, Vol. 7 (1933), pp. 1–12.

[32] George H. Chadwick, "Faunal Differentiation in the Upper Devonian," *Bull. Geol. Soc. America*, Vol. 46 (1935), pp. 305–42.

[33] Bradford Willard and Kenneth E. Caster, "Age of Devonian in Southwestern Pennsylvania," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 10 (October, 1935), pp. 1546–50.

[34] Bradford Willard, "The Devonian of Pennsylvania," *Pennsylvania Geol. Survey Bull. G 19*, 4th Ser. (1939), p. 268.

[35] Charles R. Fettke and Robert E. Bayles, *op. cit.*, pp. 87–92.



OUTLINE MAP OF
SOUTHWESTERN PENNSYLVANIA SHOWING LOCATION OF WELLS,
MEASURED SECTIONS, AND POSITION OF CROSS-SECTIONS

FIG. 2

of Philosophy degree at the University of Cincinnati.[36] Unfortunately, this work has not been published in full. However, two short papers and an abstract have been published,[37] and in these Laird states his conviction that the uppermost exposed Devonian strata of the inlier areas are Conewango in age, with the Devonian passing into Lower Mississippian sediments with little or no interruption in time.

SUBSURFACE WELL SECTIONS

Since the New Penn Development Company and others completed their first gas well on the Leo Heyn property at Summit on the Chestnut Ridge anticline in 1937, forty-six Oriskany sandstone tests have been drilled along the Chestnut Ridge and Laurel Ridge anticlines in southwestern Pennsylvania. In addition, The Peoples Natural Gas Company, in 1947 and 1948, drilled seven wells designed to test the Saxton, Allegrippis, and other lower Chemung sandstones in the broad plateau area between Laurel Ridge and the Allegheny Front. Detailed examination of the drill cuttings, which were saved at all of these wells, has yielded many excellent sections not available prior to this time. Some of these sections, in a generalized graphic form, together with additional sections in the oil- and gas-producing area west of Chestnut Ridge, are assembled into cross sections which illustrate the facies variations in the Upper Devonian sediments of southwestern Pennsylvania.

The location of the wells and measured sections used in assembling the cross sections, and the position of the cross sections in relation to the Chestnut Ridge and Laurel Ridge anticlines, the Allegheny erosional front, and the outcrop area of Upper Devonian rocks east of the front, are shown in Figure 2.

Cross section *AA′* (Fig. 3) is parallel with and approximately 9 miles west of the Allegheny Front, with the exception of the northeast end, which has been swung more toward the east and joins the famous Horseshoe Curve section as measured by Frank M. Swartz and others[38] along the Allegheny Front. The general parallelism of the Devonian strata is striking and appears to indicate that the line of this section is more or less parallel with the Devonian shoreline in this part of Pennsylvania. If this is true, probably the individual members as traced from section to section are approximately the same in age. The apparent thinning of the Devonian rocks between the Krempasky well and the Horseshoe Curve is believed to be due to errors in measuring the Horseshoe Curve section, rather than an actual thinning. The Saxton and Allegrippis members are lenticular, but their

[36] Wilson M. Laird, "The Stratigraphy of the Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *unpublished doctorate thesis, Univ. Cincinnati* (1942).

[37] *Idem*, "Devonian and Mississippian Relations in Southwestern Pennsylvania" (abstract), *Bull. Geol. Soc. America*, Vol. 50 (1939), p. 1983.
———, "Devonian and Mississippian Inliers of Southwestern Pennsylvania," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 1 (January, 1941), pp. 161–64.
———, "The Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 126* (1941).

[38] Unpublished section measured by Frank M. Swartz and others along the main line of the Pennsylvania Railroad west of Altoona, Pennsylvania. Reproduced graphically (Fig. 3) with permission of F. M. Swartz.

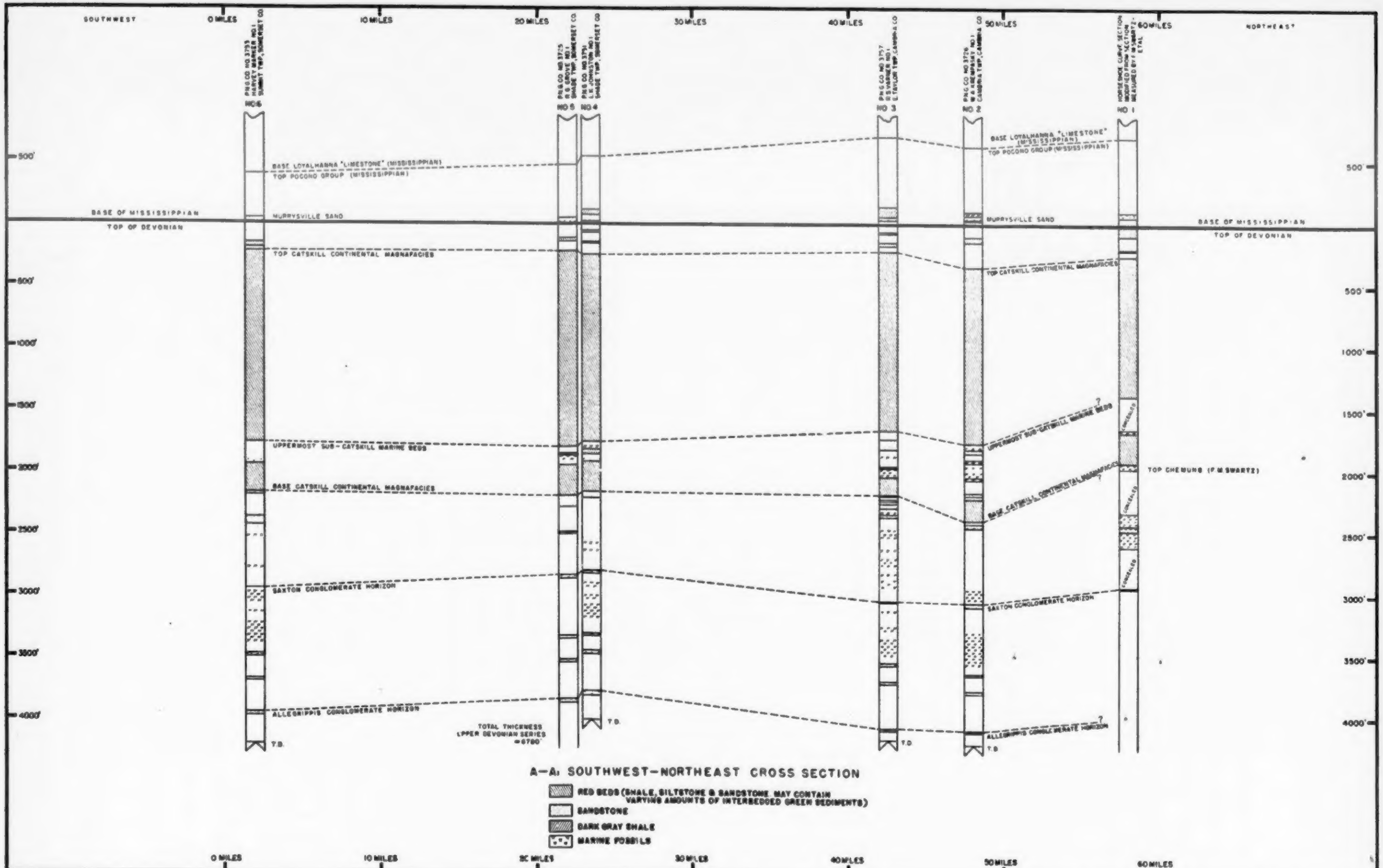

SOUTHWEST
NORTHEAST
0 MILES
10 MILES
20 MILES
30 MILES
40 MILES
50 MILES
60 MILES
BASE LOYALHANNA "LIMESTONE" (MISSISSIPPIAN)
TOP POCONO GROUP (MISSISSIPPIAN)
MURRYSVILLE SAND
BASE OF MISSISSIPPIAN
TOP OF DEVONIAN
TOP CATSKILL CONTINENTAL MAGNAFACIES
UPPERMOST SUB-CATSKILL MARINE BEDS
BASE CATSKILL CONTINENTAL MAGNAFACIES
SAXTON CONGLOMERATE HORIZON
ALLEGRIPPIS CONGLOMERATE HORIZON
TOP CHEMUNG (F.M. SWARTZ)
TOTAL THICKNESS UPPER DEVONIAN SERIES
T.D.
A—A: SOUTHWEST—NORTHEAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
DARK GRAY SHALE
MARINE FOSSILS

FIG. 3

horizons, even where the sandstones themselves are absent, are easily recognized. That part of the section below the base of Catskill continental magnafacies is similar, lithologically, to the Conneaut and Canadaway groups of the more westward sections, although here, according to Willard and Swartz, the uppermost sub-Catskill marine beds are upper Chemung in age. On the basis of lithology and interval from the base of the redbeds, the Saxton could easily be substituted for the Speechley sand; the Allegrippis for the Benson. The unnamed sandstones lying 550 feet and 650 feet below the Saxton could be the 2d and 3d Bradford sands as far as lithology and relationship with overlying and underlying rocks are concerned. The rocks above the Saxton and below the redbeds commonly, but not everywhere, exhibit the grayish red or purplish gray color characteristic of the more westward Conneaut. The rocks below the Saxton are very similar to the rocks below the Speechley farther west. In other words, during the deposition of the Conneaut and Canadaway groups of the area west of Chestnut Ridge there was a repetition of conditions which here governed the deposition of the Chemung group.

The Catskill continental magnafacies in these sections, as in all other sections where it is developed, consists of interbedded red and green shale, siltstone and sandstone, the red sediments generally comprising 75 per cent or more of the total thickness.

The fossiliferous bed directly above the sandstone correlated as Murrysville in the Horseshoe Curve section has been correlated with the Riddlesburg shale of the Broad Top area by Laird,[39] and he drew the base of the Mississippian at the base of this shale. However, Laird points out that the underlying sandstone (here correlated as Murrysville and included in the Mississippian) is barren of fossils and could as easily be included in the Mississippian as in the Devonian.

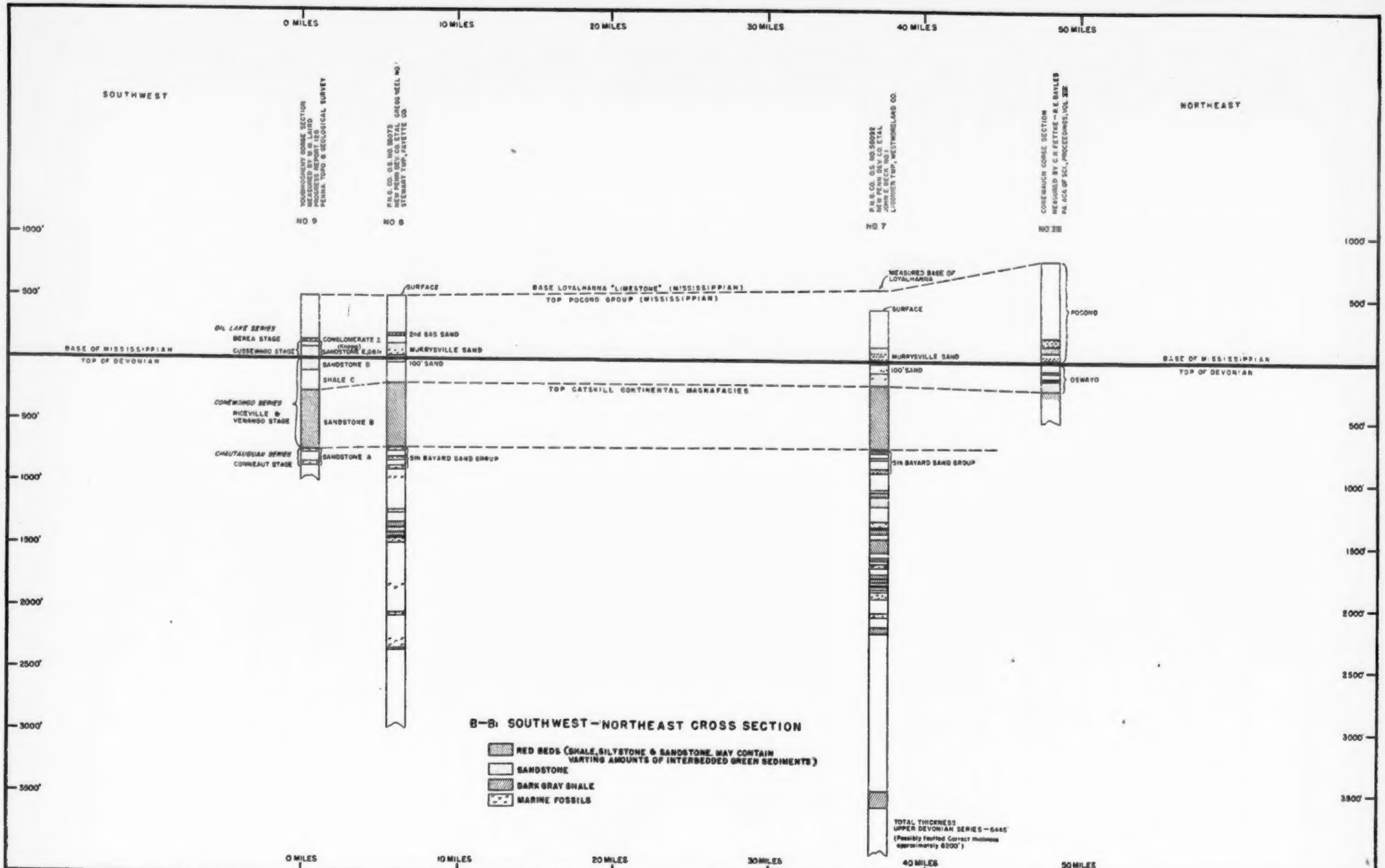
Cross section *BB'* (Fig. 4) is drawn parallel with the first and is located along the Laurel Ridge anticline. It is introduced here primarily for the purpose of correlating the measured sections at either end of the cross section with the subsurface sections as revealed by the John E. Beck No. 1 and the Greg Neel No. 1 wells, both drilled by the New Penn Development Company and others. The section at the north end of the cross section was measured by Fettke and the writer through the Conemaugh Gorge west of Johnstown in 1945.[40] The section at the south end was measured by Laird through the Youghiogheny Gorge in 1941.[41] The upper part of the section revealed by the Greg Neel No. 1 is almost an exact duplication of the section measured by Laird. The correlation of the Neel section is based on lithology and stratigraphic position, while Laird's correlation of the Youghiogheny Gorge section is based mainly on faunal evidence. In examining the Youghiogheny Gorge section in the field an error in measurement was discovered.

[39] Wilson M. Laird, "The Stratigraphy of the Upper Devonian and Lower Mississippian Southwestern Pennsylvania," *unpublished doctorate thesis, Univ. Cincinnati*, pp. 70.

[40] Charles R. Fettke and Robert E. Bayles, *op. cit.*, pp. 87–92.

[41] Wilson M. Laird, "The Upper Devonian and Lower Mississippian of Southwestern Pennsylvania," *Pennsylvania Geol. Survey Prog. Rept. 126* (1941), pp. 6–8.

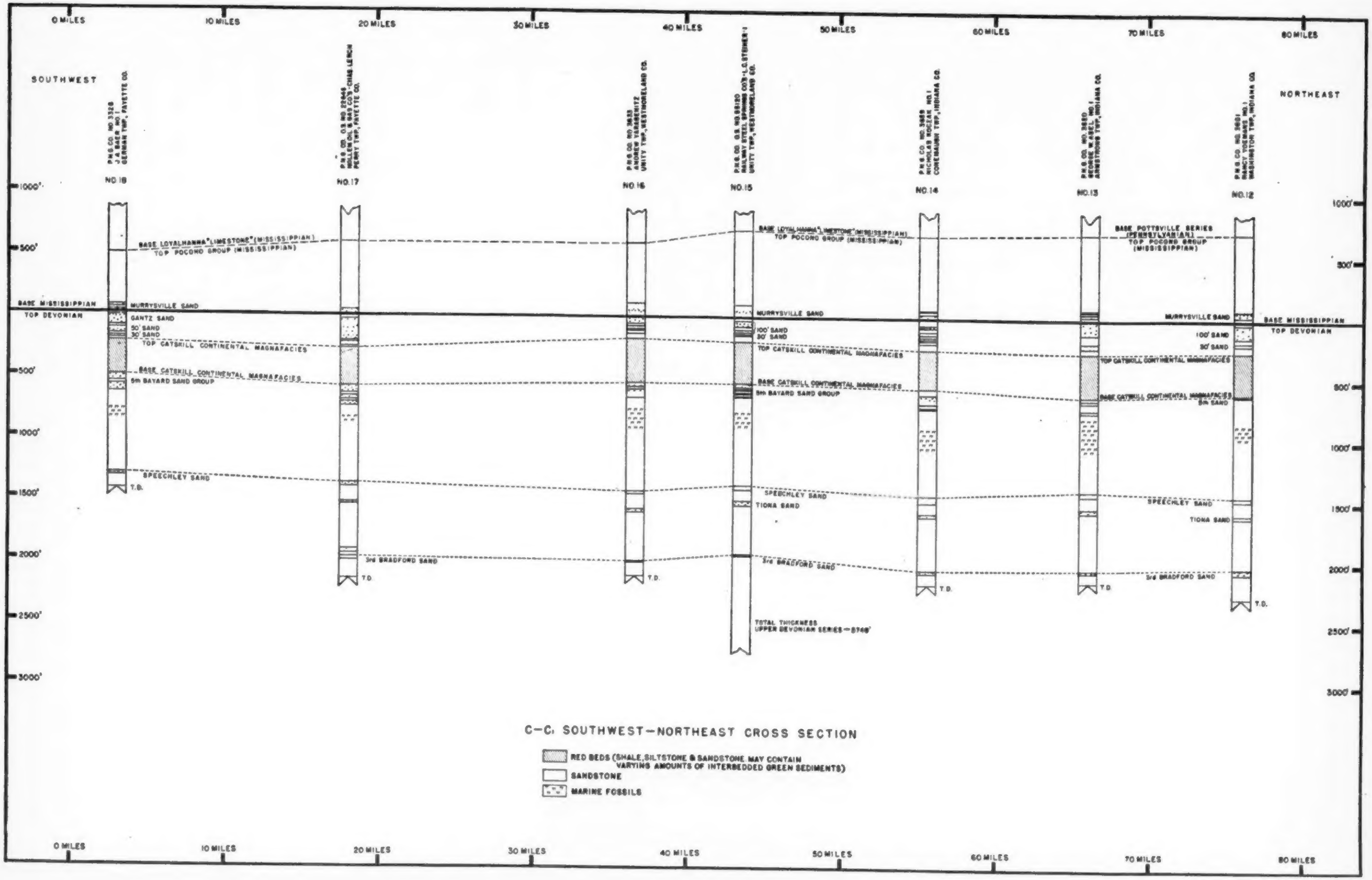
FIG. 3



B–B₁ SOUTHWEST–NORTHEAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE, MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
DARK GRAY SHALE
MARINE FOSSILS
SOUTHWEST
NORTHEAST
0 MILES
10 MILES
20 MILES
30 MILES
40 MILES
50 MILES
YOUGHIOGHENY GORGE SECTION
MEASURED BY W. R. LAIRD
PROGRESS REPORT 126
PENNA. TOPO & GEOLOGICAL SURVEY
NO 9
P.N.G. CO. O.S. NO. 58073
NEW PENN DEV. CO. ETAL GREGG WELL NO 1
STEWART TWP., FAYETTE CO.
NO 8
P.N.G. CO. O.S. NO. 56098
NEW PENN DEV. CO. ETAL
JOHN E. BECK NO. 1
LIGONIER TWP., WESTMORELAND CO.
NO 7
CONEMAUGH GORGE SECTION
MEASURED BY C. R. FETTKE – R. E. BAYLES
PA. ACA. OF SCI., PROCEEDINGS, VOL. XX
NO XII
BASE LOYALHANNA "LIMESTONE" (MISSISSIPPIAN)
TOP POCONO GROUP (MISSISSIPPIAN)
MEASURED BASE OF LOYALHANNA
SURFACE
POCONO
OIL LAKE SERIES
BEREA STAGE
CUSSEWAGO STAGE
CONGLOMERATE 2
SANDSTONE E
2nd GAS SAND
MURRYSVILLE SAND
BASE OF MISSISSIPPIAN
TOP OF DEVONIAN
SANDSTONE D
100' SAND
SHALE C
OSWAYO
TOP CATSKILL CONTINENTAL MAGNAFACIES
CONEWANGO SERIES
RICEVILLE & VENANGO STAGE
SANDSTONE B
CHAUTAUQUAN SERIES
CONNEAUT STAGE
SANDSTONE A
5th BAYARD SAND GROUP
TOTAL THICKNESS UPPER DEVONIAN SERIES – 6445'
(Possibly faulted Correct thickness approximately 6200')
1000'
500'
500'
1000'
1500'
2000'
2500'
3000'
3500'

FIG. 4

FIG. 4



SOUTHWEST
NORTHEAST
0 MILES
10 MILES
20 MILES
30 MILES
40 MILES
50 MILES
60 MILES
70 MILES
80 MILES
NO.18
NO.17
NO.16
NO.15
NO.14
NO.13
NO.12
BASE MISSISSIPPIAN
TOP DEVONIAN
MURRYSVILLE SAND
GANTZ SAND
TOP CATSKILL CONTINENTAL MAGNAFACIES
BASE CATSKILL CONTINENTAL MAGNAFACIES
5th BAYARD SAND GROUP
SPEECHLEY SAND
TIONA SAND
3rd BRADFORD SAND
T.D.
C–C, SOUTHWEST–NORTHEAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
MARINE FOSSILS

FIG. 5

Laird reported his "Sandstone J," which includes the strata between the base of the Loyalhanna and the top of his "Conglomerate I," as being 142 feet thick. By careful measurement, this interval was found to be 310 feet instead, and this figure is used in this section.

It is interesting to note the correlations here. The sand correlated as the 2d Gas sand in the Neel well, Laird has tentatively called Berea in his measured section. The underlying Murrysville, Laird has called Knapp. The 100-Foot, he has called Riceville. The 5th Bayard group is the top of his Conneaut. The correlation of the 2d Gas sand with the Berea sandstone of Ohio, the Murrysville sand with the Knapp formation of McKean County, Pennsylvania, and the 5th Bayard sand group as occurring at the top of the Conneaut was arrived at independently by the oil and gas subsurface geologist many years ago, but it is indeed comforting to have the support of the fossils.

The thickness of the Pocono group in the Conemaugh Gorge section is exceptional. No evidence of faulting could be found and, as the section is nearly completely exposed, this thickness is assumed to be correct. Structure mapping on the Loyalhanna limestone further verifies this interval.

Cross section *CC′* (Fig. 5) is parallel with the two previous cross sections and with the main structural features of the area, but is 30 miles west of the first cross section. The general parallelism of the Devonian strata is still apparent, and again the assumption is made that the individual members which can be identified in the various subsurface sections are approximately the same in age. The Catskill continental magnafacies has thinned considerably, but beneath it the more easterly sub-Catskill marine section is lithologically duplicated. Presumably the marine fossils, if they were available for inspection, would show these beds to be much younger than their eastern lithologic correlatives.

Cross section *DD′* (Fig. 6) is at right angles to the previous three sections, intersecting them as shown in Figure 2. The section is parallel with the direction of regression and is important in that it shows that the thinning of the Catskill continental magnafacies west of the Allegheny Front is not a gradual process, but happens abruptly in a relatively short horizontal distance. In the subsurface section as revealed by the John E. Beck well No. 1 on Laurel Ridge, the interval from the highest redbed to the lowest is nearly identical with the total thickness of these beds in the easternmost well a few miles west of the Allegheny Front. Presumably, near the close of Chemung time the continental facies encroached very rapidly on the west, almost reaching the position of Chestnut Ridge. Here a temporary interruption in the withdrawal occurred, and the sea gradually advanced eastward to approximately the position of the Allegheny Front. Renewed uplift of the land area prevented advance farther east, and the continental facies again encroached rapidly on the west, but this time only to Laurel Ridge. Here, throughout the remainder of Canadaway and Conneaut time, the sea and the land alternated in supremacy. However, for the sea it was a losing battle, and at the beginning of Conewango time the continental facies advanced rapidly westward, covering the offshore marine sediments deposited during Canadaway and

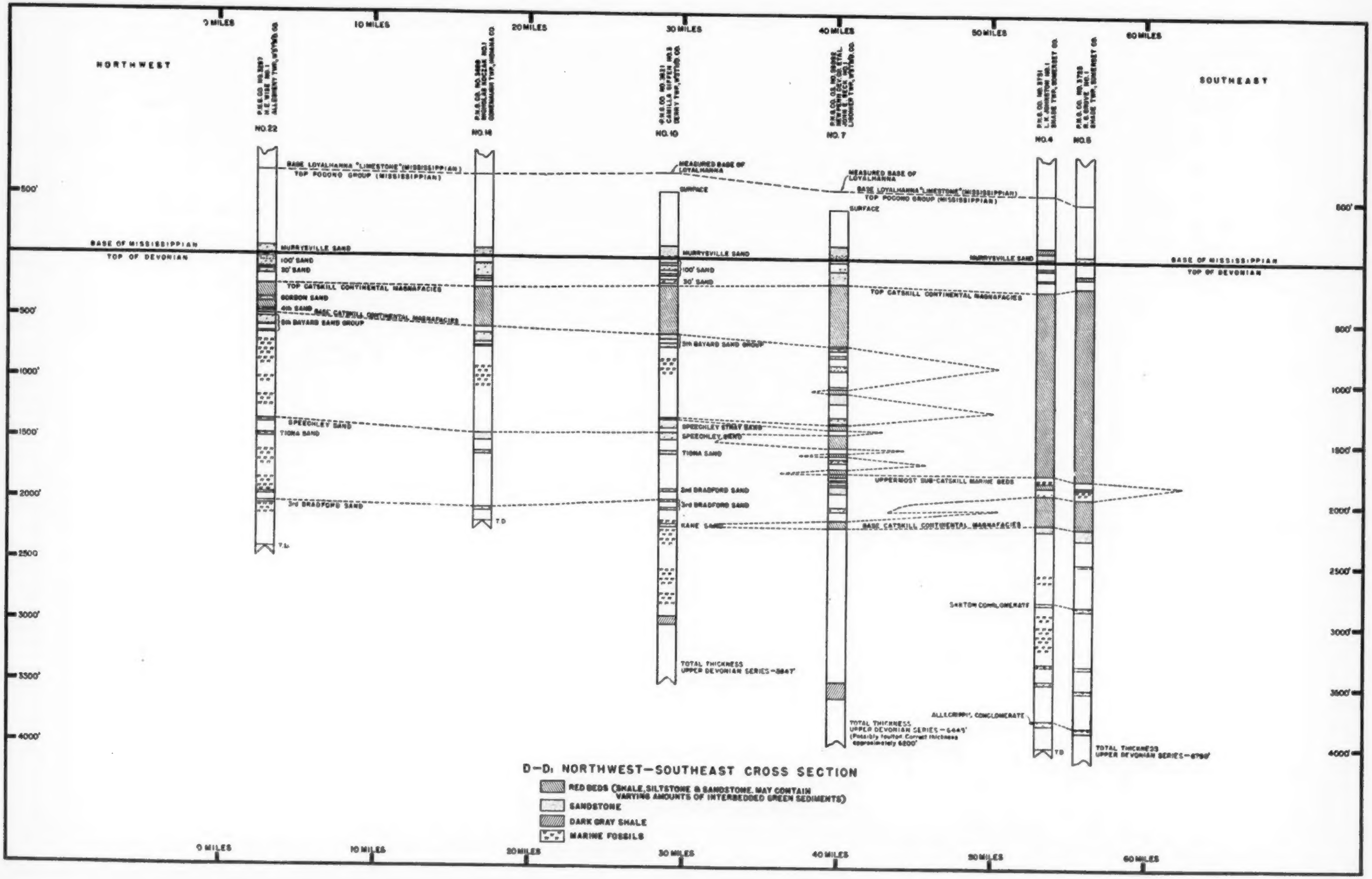

NORTHWEST
SOUTHEAST
0 MILES
10 MILES
20 MILES
30 MILES
40 MILES
50 MILES
60 MILES
NO.22
NO.14
NO.10
NO.7
NO.4
NO.5
BASE LOYALHANNA "LIMESTONE" (MISSISSIPPIAN)
TOP POCONO GROUP (MISSISSIPPIAN)
MEASURED BASE OF LOYALHANNA
SURFACE
BASE OF MISSISSIPPIAN
TOP OF DEVONIAN
MURRYSVILLE SAND
100' SAND
30' SAND
TOP CATSKILL CONTINENTAL MAGNAFACIES
GORDON SAND
4th SAND
BASE CATSKILL CONTINENTAL MAGNAFACIES
5th BAYARD SAND GROUP
SPEECHLEY SAND
SPEECHLEY STRAY SAND
TIONA SAND
2nd BRADFORD SAND
3rd BRADFORD SAND
KANE SAND
UPPERMOST SUB-CATSKILL MARINE BEDS
SAXTON CONGLOMERATE
ALLEGRIPPIS CONGLOMERATE
T.D.
TOTAL THICKNESS UPPER DEVONIAN SERIES—3847'
TOTAL THICKNESS UPPER DEVONIAN SERIES—6445'
TOTAL THICKNESS UPPER DEVONIAN SERIES—6790'
500'
1000'
1500'
2000'
2500'
3000'
3500'
4000'
D—D1 NORTHWEST—SOUTHEAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE, MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
DARK GRAY SHALE
MARINE FOSSILS

FIG. 6

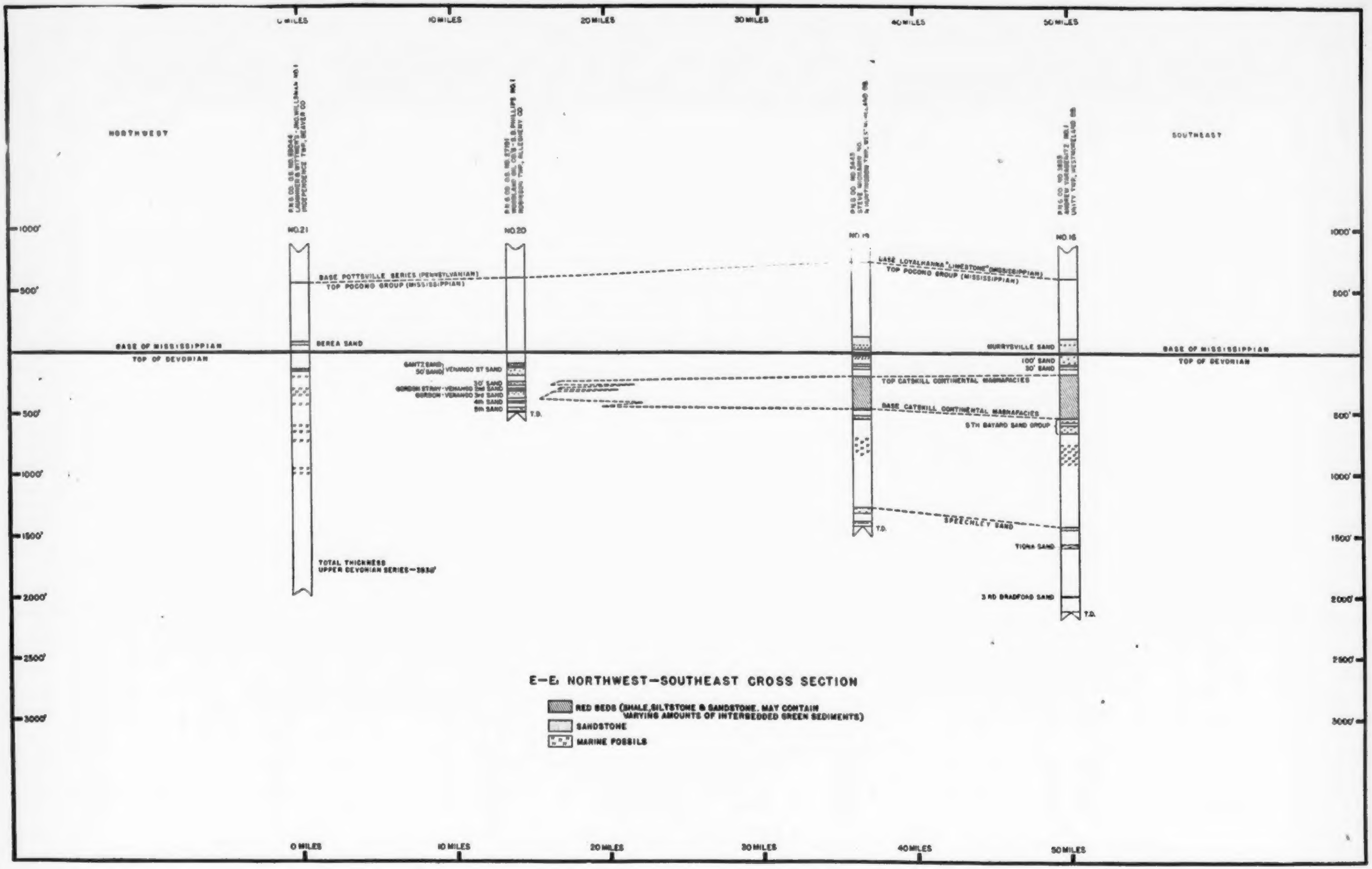

NORTHWEST
SOUTHEAST
0 MILES
10 MILES
20 MILES
30 MILES
40 MILES
50 MILES
NO. 21
NO. 20
NO. 16
BASE POTTSVILLE SERIES (PENNSYLVANIAN)
TOP POCONO GROUP (MISSISSIPPIAN)
BEREA SAND
BASE OF MISSISSIPPIAN
TOP OF DEVONIAN
MURRYSVILLE SAND
TOP CATSKILL CONTINENTAL MAGNAFACIES
BASE CATSKILL CONTINENTAL MAGNAFACIES
5TH BAYARD SAND GROUP
SPEECHLEY SAND
TIONA SAND
3 RD BRADFORD SAND
T.D.
TOTAL THICKNESS
UPPER DEVONIAN SERIES—3930'
E—E, NORTHWEST—SOUTHEAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE, MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
MARINE FOSSILS

FIG. 7

Conneaut time. The top of the Catskill continental magnafacies in southwestern Pennsylvania is nearly parallel with the top of the Devonian and is believed to represent an approximate plane of contemporaneity. Overlying the redbeds is a series of marine sediments which includes the 100-Foot sand group and the 30-Foot sand. These marine sediments have been correlated as Oswayo by Fettke and the writer and as Riceville by Laird. They are believed to have been deposited in a transgressing sea. The 5th Bayard sand group, the Speechley, Tiona, 3d Bradford, and other Upper Devonian producing sands of southwestern Pennsylvania, can not be identified with certainty in the eastern wells or along the Allegheny Front as they have passed eastward into the continental redbed facies. Further, the Saxton, Allegrippis, and other unnamed sandstones of the Allegheny Front and the eastern sections can not be identified in the western sections, having passed westward into the interbedded greenish gray shales and siltstones which underlie the producing sands.

Cross section *EE′* (Fig. 7) is a westward extension of the previous cross section, but offset 20 miles on the south. It illustrates the western terminus of the Catskill continental magnafacies. The Speechley, Tiona, 3d Bradford, and other Canadaway producing sands lose their identity the same as the Saxton and Allegrippis sandstones of the Chemung, passing westward into interbedded greenish gray shales and siltstones a short distance west of section No. 19. Section No. 20 was compiled from a study of the drill cuttings from the Woodland Oil Company's S. B. Phillips well No. 1, which was drilled in 1894 and is a few miles northeast of the old McDonald field. This is probably the first well in the Appalachian area of which a complete set of samples was saved. These were collected by I. C. White and are now a part of the collection of the West Virginia Geological Survey. The sands in this well are believed to represent offshore bars, a feature discussed in detail by Dickey, Sherrill, and Matteson in their Oil City Quadrangle report.[42] Still farther west these sands also pass into interbedded greenish gray shales and siltstones. The total thickness of the Upper Devonian series, 6,780 feet in the R. G. Grove well No. 1 at the east end of the previous cross section, has thinned to 3,930 feet in the John Willsman well No. 1 at the west end of this cross section.

Cross section *FF′* (Fig. 8) is also drawn approximately parallel with the direction of regression and illustrates the relationship of the western producing sands to the Catskill continental magnafacies as it is developed along the Allegheny Front. In section No. 8, which is the Greg Neel well No. 1, Laird's letter terminology, applied by him to his measured section in the Youghiogheny Gorge, has been substituted for the sand names. This was done to show again the relationship of these units, correlated by Laird on the basis of fossil identifications, to the subsurface sections in the western producing fields. Again, Conglomerate I, which Laird tentatively correlated as Berea, is the 2d Gas sand. Sandstones E, G, and H, which he correlated as the Knapp group, are correlated with the

[42] Parke A. Dickey, R. E. Sherrill, and L. S. Matteson, "Oil and Gas Geology of the Oil City Quadrangle, Pennsylvania," *Pennsylvania Geol. Survey Bull. M 25* (1943), pp. 23–40.

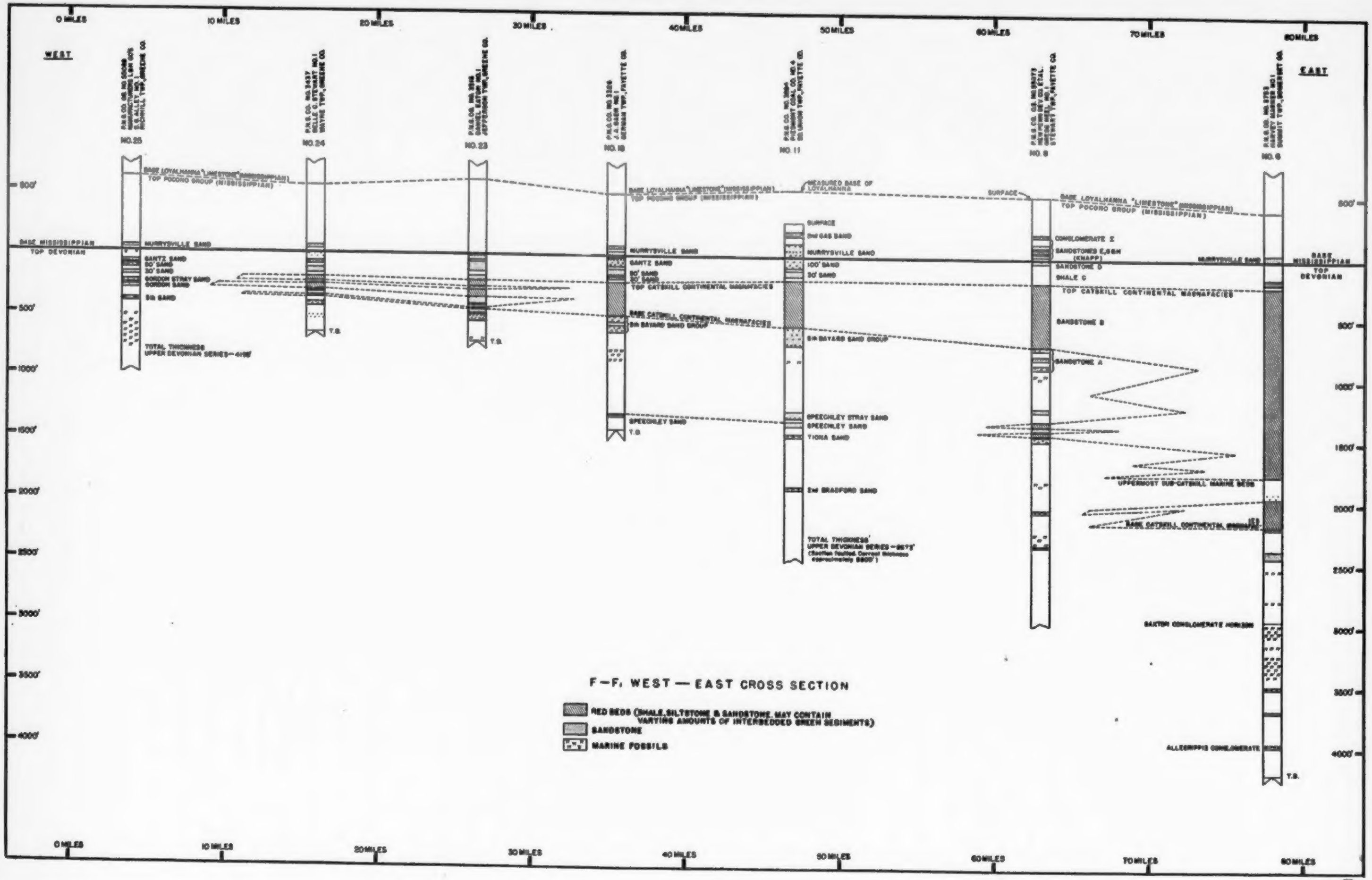

F—F, WEST — EAST CROSS SECTION
RED BEDS (SHALE, SILTSTONE & SANDSTONE, MAY CONTAIN VARYING AMOUNTS OF INTERBEDDED GREEN SEDIMENTS)
SANDSTONE
MARINE FOSSILS
WEST
EAST
BASE MISSISSIPPIAN
TOP DEVONIAN
TOP CATSKILL CONTINENTAL MAGNAFACIES
BASE CATSKILL CONTINENTAL MAGNAFACIES
UPPERMOST SUB-CATSKILL MARINE BEDS
SAXTON CONGLOMERATE HORIZON
ALLEGRIPPIS CONGLOMERATE

FIG. 8

Murrysville. Sandstone D is Riceville in age and is the 100-Foot sand. Sandstone B he considered equivalent to the Venango formation, and Sandstone A, which Laird placed at the top of the Conneaut group is the 5th Bayard sand group of the producing area on the west.

Section No. 11 is at Summit on the Chestnut Ridge anticline and is in the vicinity of the often disputed Upper Devonian beds exposed in the Summit inlier. The sandstones here correlated as the 2d Gas, Murrysville, 100-Foot, and 30-Foot sands are lenticular in this area and commonly consist of interbedded sandstones and shales containing marine fossils as exposed along U. S. Route 40 at Summit. These beds have been the cause of controversy for many years. Laird, in his unpublished work, includes a section measured along U. S. Route 40 in this area. His correlations of the section, based on faunal evidence and stratigraphic position, bear the same close relationship to the many subsurface sections in the area as his Youghiogheny Gorge section bears to the Greg Neel well on Laurel Ridge.

FIG. 8

CONCLUSIONS

Study of these cross sections indicates the following conclusions. 1. The direction of regression of the Upper Devonian seas in western Pennsylvania was northwestward, the shoreline being approximately parallel with the present Allegheny Front and with the major structural features of the area. 2. The Upper Devonian producing sands of western and southwestern Pennsylvania which are marine in origin, pass eastward into the Catskill continental magnafacies as it is developed along the Allegheny Front. 3. The Saxton, Allegrippis, and other Chemung sandstones developed along the Allegheny Front pass westward into interbedded greenish gray shales and siltstones beneath the producing sands. However, these sandstones were deposited under environmental conditions like those prevailing during deposition of the Speechley-3d Bradford group of producing sands on the west; therefore, it is possible that the plateau area east of Laurel Ridge and west of the Allegheny Front, where these sandstones are present, represents a potential gas-producing area. Drilling results to date, however, have not been encouraging. 4. The Catskill continental magnafacies, as developed along the Allegheny Front, is equal in age to the combined Canadaway, Conneaut, and Conewango groups of western Pennsylvania. However, it is possible that careful restudy of the higher sub-Catskill marine fossils along the Front would show that the rocks containing them are lower Canadaway rather than upper Chemung in age. 5. The often disputed Upper Devonian rocks exposed in the inlier areas of southwestern Pennsylvania are Conewango in age, and these sediments, deposited in a transgressing sea, pass into Mississippian sediments with little or no interruption in time. 6. The top of the Catskill continental magnafacies in western and southwestern Pennsylvania represents an approximate plane of contemporaneity, whereas the base becomes progressively younger westward. However, the advance of the shoreline over that part of the area west of Chestnut Ridge, including present producing fields, was rapid, and the time lag is believed to be relatively slight.

ULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGIS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1704-1730, 9 FIGS., 2 TABLES

PETROLOGY AND PALEOGEOGRAPHY OF GREENBRIER FORMATION[1]

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ABSTRACT

This paper describes the petrology and paleogeography of the Mississippian Greenbrier formation as determined from study of well samples, insoluble residues, heavy minerals, and thin sections. In the Greenbrier formation, clastic limestone beds composed of lime sand, oölites, and quartz sand alternate with beds of fine-grained limestone in which clastic texture is indistinct or can not be recognized. The clastic limestones appear to be nearshore sediments and in part are probably ancient bar, beach, channel, and dune deposits and have the shapes and trends characteristic of such deposits. Approximately half of the production of oil and gas from the Greenbrier formation is from clastic limestones; half from dolomite and dolomitic limestone, which are largely confined to the basal 20–30 feet of the Greenbrier formation. This basal zone appears to transgress both time units and structure. The dolomite clearly replaces limestone. Four methods by which magnesium-bearing waters could be introduced into the formation are suggested and the probable pattern of dolomitization resulting from each method is considered.

The quartz sand in the Greenbrier was derived from two or more different sources on the north. Neither earlier Mississippian nor Upper Devonian sands of West Virginia and adjacent parts of Ohio and Pennsylvania were important sources of the quartz sand.

INTRODUCTION

In 1943, as part of an expanded program of investigations in the field of petroleum geology, the United States Geological Survey began regional studies of oil- and gas-producing formations in the Appalachian basin. Regional variations in thickness, areal distribution, mineralogy, texture, and other properties of the formations were to be investigated. From them, the paleogeography, conditions of deposition, sources of sediment, and post-depositional changes in the formations were to be inferred, and areas generally favorable or unfavorable for oil and gas exploration were to be outlined. Maps and accompanying texts describing the Berea sandstone already have been published by the Geological Survey as *Preliminary Maps 9, 29, 39, 49, 58, 59, 69, 79, and 89* and *Preliminary Chart 21* of the Oil and Gas Investigations Series.

The present paper summarizes information about the Greenbrier formation of West Virginia and its equivalents in adjacent parts of Pennsylvania and Ohio. Because the unit is essentially a continuous lithologic unit in the subsurface in the area discussed it is for convenience referred to as the Greenbrier formation throughout the paper. This use of the term does not imply that the name Maxville limestone which is used for the equivalent unit in parts of Ohio, or that the name Loyalhanna limestone which is used for the partial equivalent of the Greenbrier

[1] Read before the Association at Pittsburgh, October 4, 1948. Manuscript received, February 14, 1949. Published by permission of the director of the United States Geological Survey.

[2] University of Cincinnati. The writer is indebted to the West Virginia Geological Survey and the West Virginia University for office and laboratory space, the use of much laboratory equipment, and access to the Survey collection of well samples. Particular thanks are due to J. H. C. Martens whose unpublished sample examinations were made freely accessible to the writer. Insoluble residues and heavy-mineral samples were prepared by Elaine Cather. Thanks are due also to the companies and individuals responsible for collection of well samples and cores, without which this investigation could not have been made.

in Pennsylvania is being replaced. Drillers refer to the subsurface Greenbrier and equivalents as the "Big lime."

Most of the data were obtained from examination and study of (1) drill cuttings and insoluble residues from 12 wells in separate areas of West Virginia and 1 well in southeastern Ohio; (2) 1 cored section in southeastern Ohio; (3) heavy minerals from 21 wells and 4 outcrop localities in West Virginia and southwestern Pennsylvania; and (4) several thin sections of rocks in the formation from wells in West Virginia. Sample studies by Martens[3] provide additional basic data. The results of this preliminary investigation are being published at this time in order to make the data and conclusions available. Much additional work will be necessary to solve some of the problems that have been encountered.

Beds composed of quartz sand, lime sand[3a], and oölites in varying proportions occur at several horizons in the Greenbrier formation. These beds are calcareous sandstones in which the sand grains, of both quartz and carbonate, were transported to their place of deposition by waves, or by currents of wind or water. These fragmental or clastic beds occur at definite horizons in the Greenbrier formation and are separated by beds of fine-grained limestone in which no quartz sand occurs and in which the outlines of lime sand grains and oölites are indistinct or absent.

The clastic textures indicate that at least part of the Greenbrier formation was deposited in the same way as pure quartz sands like the Berea. The clastic deposits of the Greenbrier represent accumulations along old beaches, bars, dunes, or river channels. Therefore, the trends, thickness, and shape of the clastic limestone beds should be similar to the trends, thickness, and shape of beds of pure quartz sand in other formations. Nearly half of the production of oil and gas from the Greenbrier formation is from clastic beds. Consequently, the importance of recognizing clastic texture and understanding its meaning can not be overemphasized as an aid in prospecting for new fields or extending old ones.

Almost all other production from the Greenbrier formation is from a basal dolomite or dolomitic zone whose origin may have been controlled in part by structure and in part by the original distribution of porous clastic limestone. Evidence indicates that the dolomite has secondarily replaced the limestone and that magnesium was introduced into the formation subsequent to its deposition. Four methods are suggested by which the magnesium could have been introduced and concentrated in a relatively thin basal zone that cuts across sedimentary units.

[3] James H. C. Martens, "Well-Sample Records," *West Virginia Geol. Survey*, Vol. 17 (1945), p. 889.

———, "Petrography and Correlation of Deep-Well Sections in West Virginia and Adjacent States," *ibid.*, Vol. 11 (1939), p. 225.

[3a] The term "lime sand" as used in this paper refers to a limestone composed of grains of calcite, dolomite, or other carbonates of sand size (2 mm.–1/16 mm.) that have been transported to their final place of deposition. Except for composition, these lime-sand grains are similar to quartz or feldspar sand grains that make up ordinary sandstones.

Study of the heavy minerals indicates that the quartz sand in the Greenbrier formation was derived from at least two sources, but that these sources did not furnish quartz sand to the Greenbrier formation at the same time. Also, the heavy minerals provide criteria by which the "Big lime" can be differentiated from the Big Injun and Keener sands below and the basal sands of the Pottsville above. Further, the heavy minerals indicate that no significant part of the quartz sands in the Greenbrier formation was derived by erosion from the Big Injun or Keener sands. Martens'[4] conclusion that the Greenbrier limestone overlies an unconformity of considerable magnitude is confirmed.

The earliest deposits of the Greenbrier that are still preserved accumulated in southeastern West Virginia. A low landmass lay northwest of this area of deposition. Whether another landmass lay southeast and formed the southeastern margin of a relatively shallow, northeast-southwest-trending epicontinental basin of deposition is not known. The writer has no evidence that such a landmass existed on the southeast during the time the Greenbrier formation was accumulating. Consequently, the Greenbrier deposits may represent marginal accumulations in an ocean rather than in an inland sea.

Repeated transgressions and regressions of the sea or ocean occurred while the Greenbrier formation was being deposited, and had the net effect of moving the shoreline farther and farther northwest. Clastic limestones were deposited in turbulent waters near the shores; fine-grained limestones, in which clastic textures are indistinct or absent, in quieter water farther from the shore. Each period of transgression and regression is represented by a thin wedge of clastic sediments extending southeastward into the finer-grained limestones.

STRATIGRAPHY

DISTRIBUTION AND THICKNESS OF GREENBRIER FORMATION

At its outcrop near Bluefield in southeastern West Virginia, the Greenbrier formation is slightly more than 1,000 feet thick. In the subsurface north, northwest, and west the formation thins in a short distance, and, in southeastern Ohio, northwestern West Virginia, and southwestern Pennsylvania, the original thickness ranges from 125 to 200 feet. In part of Wood County in northwestern West Virginia the Greenbrier formation is absent due to erosion. In a belt 5–20 miles wide east and south of this area where the formation is absent, part of the Greenbrier was removed by erosion during late Mississippian or early Pennsylvanian time. In this belt the thickness at few places exceeds 125 feet and varies greatly in short distances probably due both to its deposition on an uneven surface and to pre-Pennsylvanian erosion. As pointed out by Martens, drillers' logs do not give the true thickness of the Greenbrier formation in much of West Virginia and southwestern Pennsylvania because some of the sandy basal phases of the formation are commonly logged as an underlying sand.

[4] *Op. cit.* (1939), p. 21.

In the subsurface the Greenbrier extends to Ohio, where it was named the Maxville limestone from outcrops near the village of that name in Perry County. In Ohio, outcrops of the Maxville limestone are confined to the southeastern part of the state. In both outcrop and subsurface the formation is patchy in distribution and variable in thickness. In Kentucky, where the equivalent of the Greenbrier is recognized under several surface and subsurface names, the formation extends southwestward across the state.

In southwestern Pennsylvania, the equivalent of the Greenbrier formation is present in Greene, Fayette, and parts of Washington, Westmoreland, Indiana, Cambria, and Allegheny counties. In part of this area the Mauch Chunk shale and part of the Greenbrier formation have been removed by pre-Pennsylvanian erosion. In Pennsylvania the basal 80 feet or so of the formation is known as the Loyalhanna limestone. It is sandy and is commonly logged by the driller as part of the underlying sand.

RELATIONS TO FORMATIONS ABOVE AND BELOW

The relation of the Greenbrier formation to the beds above and below is shown in part by the sections in Figure 1. In the northwest part of West Virginia and in all of Pennsylvania and Ohio where the unit occurs, it rests unconformably on Lower Mississippian sandstones and shales. As exposed in Pennsylvania it rests on the Burgoon sandstone member of the Pocono formation. In the subsurface in West Virginia and Ohio, it rests normally on Lower Mississippian sandstones to which the names Big Injun and Keener sands have been applied at different places by drillers. Binocular examination and heavy-mineral studies made in this investigation show that the Keener sand as used by the drillers may represent (1) a sandy basal or near-basal phase of the Greenbrier; (2) a non-clastic dense limestone in the Greenbrier; (3) the upper part of the Big Injun sand; or (4) a siltstone or shale below the Greenbrier. In West Virginia, the term Keener sand does not apply to a widespread correlative producing zone between the Greenbrier and Big Injun, although locally the term may be useful for indicating a zone that has recognizable characteristics of production. In Belmont, Monroe, and Noble counties of eastern Ohio, a coarse or pebbly sand below the Greenbrier and separated from the Big Injun by a shale break has been called Keener. Petrographically this sand is similar to the Big Injun.

In southern West Virginia and southeastern Kentucky the Greenbrier rests on the Maccrady shale, a relatively thin series of red shales and siltstones known locally to the drillers as Red Injun. In northeastern and central West Virginia the Greenbrier rests unconformably on shales and siltstones some of which are Lower Mississippian in age, and some of which may be Devonian.

In most of West Virginia and in parts of Pennsylvania and Kentucky, the Greenbrier is overlain conformably by the Mauch Chunk shale. The basal part of the Mauch Chunk is soft caving shale, 30 feet or less in thickness, known by the drillers as the Pencil Cave. In some parts of West Virginia the Pencil Cave

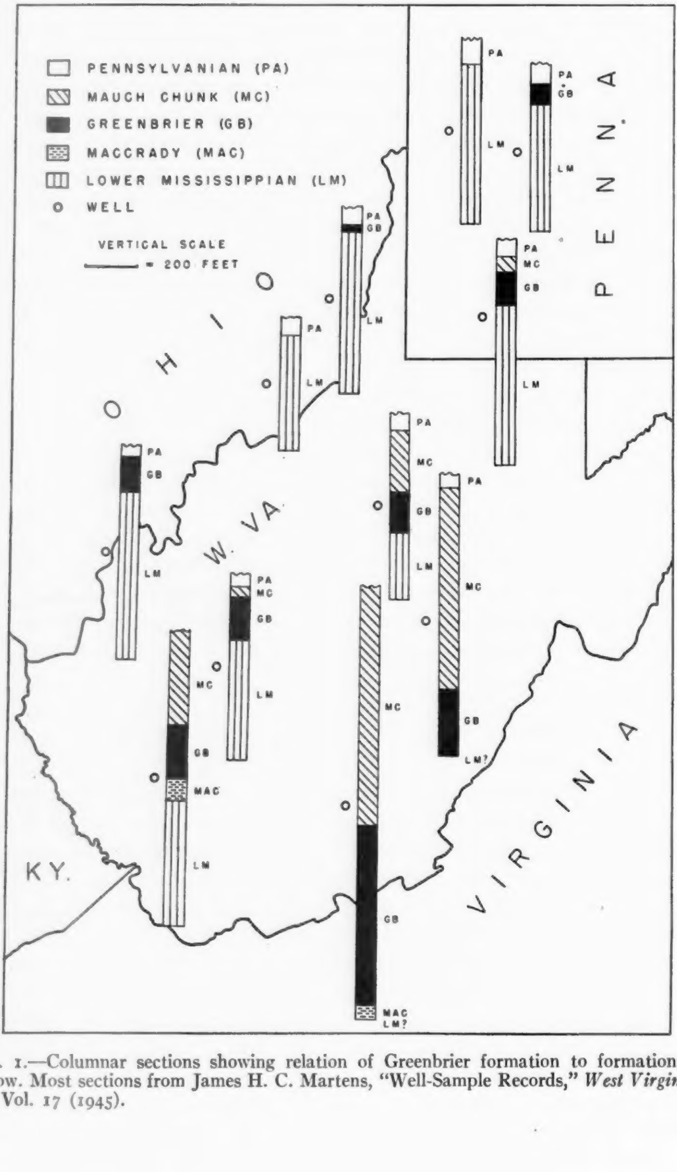

FIG. 1.—Columnar sections showing relation of Greenbrier formation to formations above and below. Most sections from James H. C. Martens, "Well-Sample Records," *West Virginia Geol. Survey*, Vol. 17 (1945).

TABLE I

NAMES AND LOCATIONS OF WELLS USED IN THIS INVESTIGATION

Symbol	*Well Name*	*Company*	*District or Township*	*County*	*Permit No.*
		INSOLUBLE RESIDUES			
BO	Boone Co. Coal Corp. No. 15	Boone Co. Coal Corp.	Logan	Logan	60
FC	Federal Coal Co. No. 2 (1110)	Godfrey L. Cabot, Inc.	Jefferson	Nicholas	21
GN	Guinn, C. E., No. 1 (1115)	Godfrey L. Cabot, Inc.	Richmond	Raleigh	36
HO	Hoover, W. W., & Davis, J. W., No. 1	Tri State Oil & Gas Co.	Hacker Valley	Webster	1
MF	Milans Fork Smokeless Coal Land Co., No. 13	Ravenscliff Dev. Co.	Slab Fork	Wyoming	11
S	Sommerville, Maud, No. 1	Cody	Addison	Gallia	Ohio
WZ	Wilson Coal Land Co., No. 36 (694)	Owens, Libbey-Owens Gas Dept.	Grant	Wayne	
		INSOLUBLE RESIDUES AND HEAVY MINERALS			
BA	Barr Tract, No. 24	South Penn Natural Gas Co.	Grant	Wetzel	321
CS	Casto, G. W., No. 1 (521)	W. Va. Gas Corp.	Union	Putnam	272
PA	Patterson, W. C., No. 1 (1523)	Carnegie Natural Gas Co.	Burning Springs	Wirt	91
RO	Roberts, Nora V., No. 5963	Hope Natural Gas Co.	Center	Gilmer	406
W	Wingfield, Mary C., No. 1	Benedum-Trees Oil Co.	Elk	Kanawha	155
WM	Woodal and Morton, No. 1 (525)	W. Va. Gas Corp.	Grant	Cabell	428
		HEAVY MINERALS			
CB	Carothers, G. R., No. 1 (3298)	Peoples Natural Gas Co.	Patton	Allegheny	Pa.
FI	Fitzgerald, A. M., No. 1 (304)	Cumberland & Allegheny Gas Co.	Mead	Upshur	94
GR	Gribble, C. S. (8517)	Hope Natural Gas Co.	Grant	Harrison	79
HD	Hardman, A. & N., No. 1	South Penn Natural Gas Co.	Sherman	Calhoun	794
HE	Heinzman, J. W., No. 4053	United Fuel Gas Co.	Curtis	Roane	19
HU	Hutchinson, O. C. & W. H., No. 1	A. D. Prunty	Salt Lick	Braxton	131
KR	Krenn, Joseph, No. 10	South Penn Natural Gas Co.	Freemans Creek	Lewis	58
MS	Mason, D. Bruce, No. 2 (6129)	Pittsburgh & W. Va. Gas Co.	Booths Creek	Taylor	17
OR	Orem, W. H., No. 1 (1200)	New Penn Development Co.	Harris	Wood	72
PK	Parks, Anna E., No. 1 (6114)	Pittsburgh & W. Va. Gas Co.	Southwest	Doddridge	98
PT	Pratt-Tennant No. 3	South Penn Natural Gas Co.	Clay	Monongalia	151D
SY	Schmittau, George	John T. Galey	Hampton	Allegheny	Pa.
WS	Wise, H. E., No. 1 (3287)	Peoples Natural Gas Co.	Allegheny	Westmoreland	Pa.
WT	Wilt, Fred, No. 4	South Penn Natural Gas Co.	Dekalb	Gilmer	536
WX	Williams, Joseph, No. 7	South Penn Natural Gas Co.	Ellsworth	Tyler	141
		CORE			
AI	Addison No. 10a	Jones & Laughlin Ore Co.	Addison	Gallia	Ohio

is overlain, and is in some places replaced, by a sandstone 60 feet or less in thickness that is locally productive. Above this is the "Little lime," a fossiliferous partly clastic, dark gray limestone, 5–40 feet thick. The "Little lime" is overlain by interbedded greenish and reddish shales, sandstones, siltstones, and limestones which in southeastern West Virginia attain a thickness of 3,400 feet. In northeastern West Virginia and southeastern Ohio where the Mauch Chunk has been removed by erosion, or was never deposited, sands of the Pottsville formation lie on the eroded surface of the Greenbrier.

PETROGRAPHIC, MINERALOGIC, AND TEXTURAL DATA

DISTRIBUTION OF QUARTZ SAND IN GREENBRIER

Drill cuttings and insoluble residues from samples through the Greenbrier formation were examined from 12 wells in separate areas in West Virginia and 1 well in Ohio. Also, the percentages of sand in samples from sandy strata of 6 wells in northern West Virginia were obtained as part of the heavy-mineral investigations. The well names and locations from which samples used in the insoluble-residue and heavy-mineral studies were obtained are given in Table I, and the locations are plotted in Figures 2 and 5.

The insoluble residues were prepared by dissolving the carbonate from

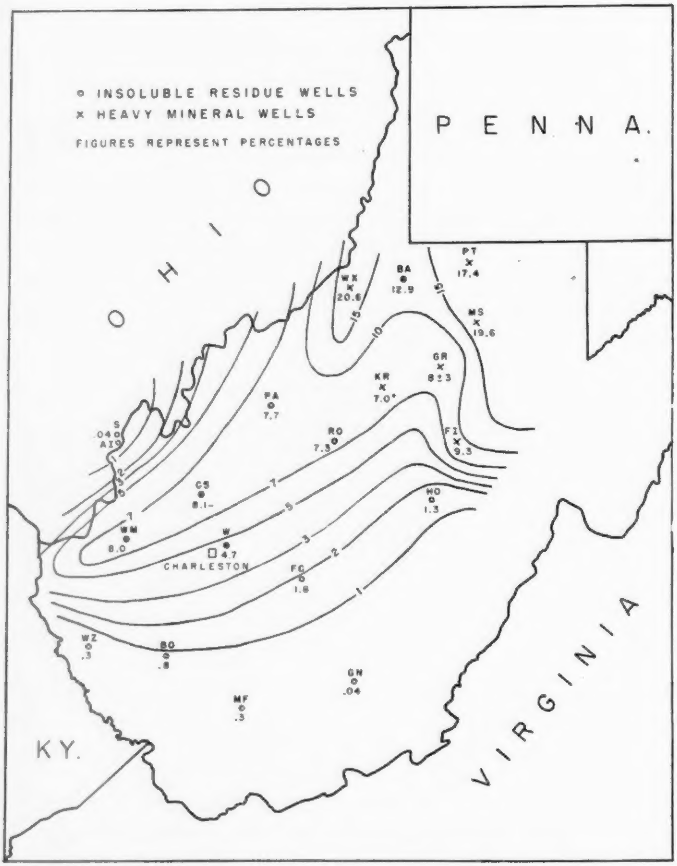

FIG. 2.—Map showing lines of equal percentage of quartz sand in Greenbrier formation. Letter symbols at locations of wells correspond with those shown in Table I.

weighed amounts of each sample in hot 3N hydrochloric acid. The residues were weighed and the percentages of quartz sand, chert, anhydrite, shale, silt, and other components were estimated from binocular examination of the residues. The percentages of quartz sand in each entire sample, and in the entire Greenbrier section at each well, were calculated. For the wells in which only the sandy strata were sampled for heavy-mineral studies, the minimum percentages of sand in the entire Greenbrier section were calculated. After study of Martens' sample logs of these wells, the probable percentages of sand in the entire Greenbrier section were estimated. These percentages are not as accurate as those

determined by the insoluble-residue studies but certainly are comparable with them. In Figure 2 the percentage for each well was plotted and lines of equal percentage of sand were drawn.

As shown in Figure 2, the quartz sand in the Greenbrier formation is distributed according to a definite pattern. The highest percentage of sand occurs in an elongate tongue extending approximately southwest from the southwest corner of Pennsylvania. The sand percentage in the northern part of the tongue is more than double that in its central and southern part. What appears to be a second, smaller tongue lies east of the one described.

Southeastward from the axis of the major tongue the percentage of quartz sand decreases. Well records and an isopach map of part of West Virginia published by Martens[5] show that the Greenbrier formation thickens in this direction, and if isopach lines were drawn they would approximately parallel the lines of equal percentage of sand shown in Figure 2. The decreased percentage of quartz sand is not due to distribution of the sand through a greater thickness of the formation; such distribution would result in a sand percentage decrease to approximately one-fifth. The decrease is nearly to one-fortieth. Northwest of the axis the quartz-sand percentage decreases more markedly than on the southeast. This decrease in quartz sand on the northwest is substantiated by observations made on the outcrop of the Maxville limestone in south-central Ohio, and of a core of the complete Greenbrier section from the Jones and Laughlin Ore Company's Addison hole 10a (AI) in Addison Township, Gallia County, Ohio.

DISTRIBUTION OF CLASTIC LIMESTONE

In examining the well cuttings, particular attention was given to differentiating clastic limestones composed of lime sand and oölite grains, and limestones in which clastic textures were indistinct or not recognizable. For each well the percentage of the Greenbrier section showing lime sand or oölites was calculated. These data, supplemented by the percentage of oölitic limestone at three measured outcrop sections,[6] were plotted and lines of equal lime sand and oölite percentage were drawn as shown in Figure 3.

As might be expected, the patterns of the lines in Figures 2 and 3 are somewhat similar. The high percentages of lime sand and oölites occur in a belt diverging only slightly in direction from the belt of the highest quartz sand percentages. Like the percentage of quartz sand the percentage of oölites and lime sand decreases both southeast and northwest of this axis. In central West Virginia, however, the lines indicating equal lime sand and oölite content bulge southward, perhaps indicating a secondary axis of high lime sand and oölite concentration diverging from the main axis.

[5] J. H. C. Martens, "Possibility of Shaft Mining of Greenbrier Limestone," *West Virginia Geol. Survey Rept. Investig. 6* (1948). 18 pp.

[6] J. B. McCue, J. B. Lucke, and H. P. Woodward, "Limestones of West Virginia," *West Virginia Geol. Survey*, Vol. 12 (1939), pp. 29–42.

The vertical distribution of clastic and non-clastic limestone in the Greenbrier formation also follows definite patterns. Along the high-percentage axis of Figure 2, where the Greenbrier is 125–175 feet in thickness, clastic limestones predominate in the lower half of the formation; non-clastic ones in the upper half. In the upper half, however, several rather inconspicuous but persistent beds of quartz sand, lime sand, and oölites alternate with the non-clastic or indistinctly

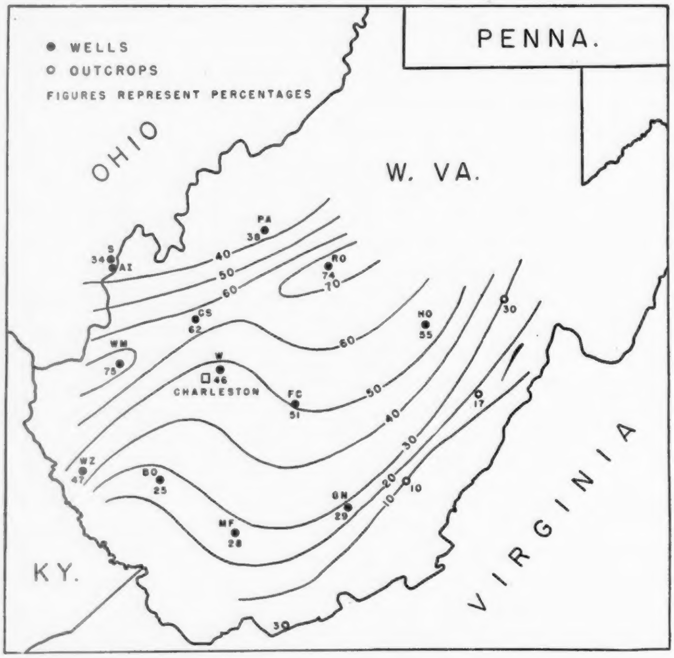

FIG. 3.—Map showing lines of equal percentage of oölites or lime sand grains in Greenbrier formation. Letter symbols at locations of wells correspond with those shown in Table I.

clastic beds. The lower half of the formation appears to contain similar alternations, but the clastic beds are much thicker. The alternation of clastic and non-clastic beds is shown in Figure 4. In the Patterson well (PA) three alternations of clastics and non-clastics occur; in the Roberts well (RO) there are four. Farther southeast, in the Hoover and Davis well (HO) six or seven repetitions of these clastic and non-clastic couplets occur. In the Hoover and Davis well the couplets range in thickness from 27 to 43 feet, averaging 35 feet.

The three clastic and non-clastic couplets at the Patterson well (PA) are correlated with the upper three couplets in the other two wells. The fourth couplet in the Roberts well (RO) is correlated with the fourth couplet in the Hoover

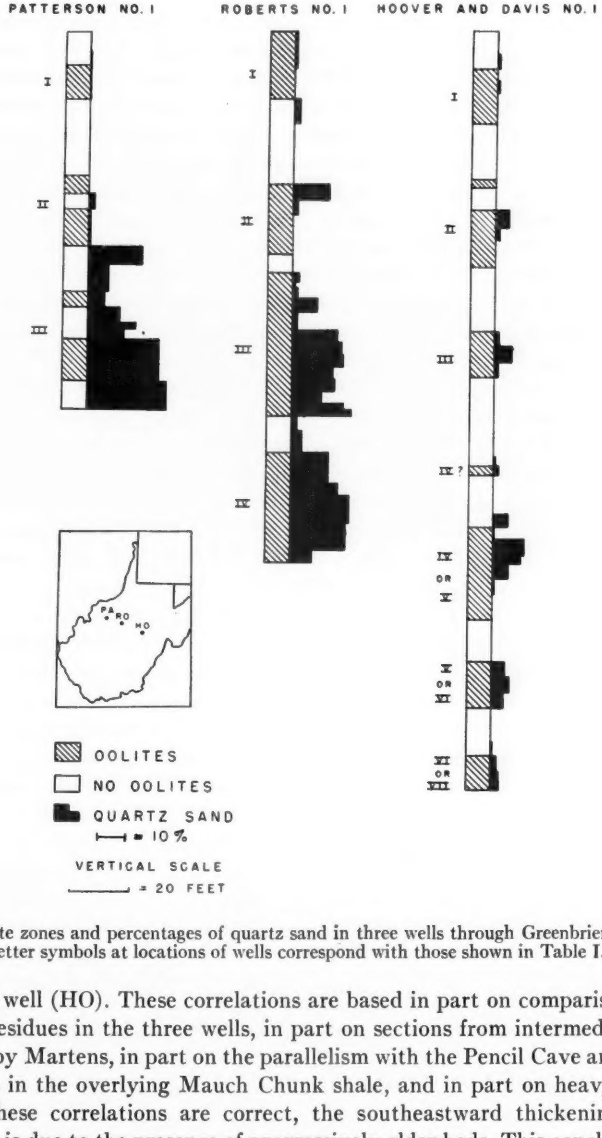

FIG. 4.—Oölite zones and percentages of quartz sand in three wells through Greenbrier formation. Letter symbols at locations of wells correspond with those shown in Table I.

and Davis well (HO). These correlations are based in part on comparison of the insoluble residues in the three wells, in part on sections from intermediate wells examined by Martens, in part on the parallelism with the Pencil Cave and "Little lime" beds in the overlying Mauch Chunk shale, and in part on heavy-mineral data. If these correlations are correct, the southeastward thickening of the Greenbrier is due to the presence of progressively older beds. This conclusion was reached by McCue, Lucke, and Woodward from study of outcrop sections.[7]

[7] McCue, Lucke, and Woodward, *op. cit.*

In southern and southwestern West Virginia the vertical distribution of clastic and non-clastic limestone beds is generally similar to that farther north. At the Gwinn well (GW), where the Greenbrier section is 672 feet thick, at least two clastic beds containing small amounts of quartz sand occur in the basal 100 feet of the formation. In this well certainly nine and possibly thirteen pairs of clastic and indistinctly clastic beds are present. In the Milans Fork Powder Company's well No. 1 (MF) eight couplets occur, and in the Boone County Coal Corporation's No. 14 (BO) at least five couplets can be recognized.

In southern West Virginia, the correlation of individual beds over wide areas has not been possible, even with the aid of the intermediate wells described by Martens. In fact, comparison of the sections in closely spaced wells suggests that the clastic beds in this area are lenticular, possibly being long, narrow shoestrings having an approximate northeast-southwest trend.

The Maud Sommerville No. 1 (S) and Addison 10a (AI) wells control the lines of equal percentage of lime sand and oölites northwest of the high-clastic axis, shown in Figure 3. The Sommerville well, which shows a much smaller percentage of quartz sand, lime sand, and oölites than wells southeast and south, is the only control for the lines of equal quartz sand percentage shown in Figure 2.

Do the limestone beds in the Sommerville and Addison wells represent a northwestward extension of the dominantly non-clastic upper half of the Greenbrier, do they represent the entire section, or do they represent more Greenbrier than is present on the southeast? The evidence now available is inconclusive. So little quartz sand is present in the Sommerville and Addison wells that quartz sand and the heavy minerals in it can not be used for correlation. Two and perhaps three oölite-bearing beds are present in the Sommerville and Addison wells. The presumption is that they are correlative with the upper clastic beds in the wells on the southeast. Because the bed-to-bed correlation is necessarily tentative, the possibility that some of the clastic beds in the Sommerville and Addison wells may be older than of the clastic beds on the southeast can not be eliminated. Study of samples from additional wells is needed.

QUARTZ SAND

Some beds of the Greenbrier formation are composed almost entirely of quartz sand, but more commonly such sand is mixed with rounded lime and oölite grains. At the outcrop some of the clastic beds show well developed cross-bedding, thereby indicating deposition in relatively shallow water or in sand dunes. The larger quartz grains are characteristically well rounded and frosted. The rounding indicates a long period of abrasion prior to deposition. Probably the sand passed through several cycles of erosion, transportation, and deposition before its final accumulation in the Greenbrier. The rounding implies that the quartz sand was derived from earlier Paleozoic sandstones.

Examination of several thin sections of sandy limestone from the Barr Tract well No. 24 (BA) indicates that the quartz sand of the third clastic zone was de-

rived originally from several rock types. About half of the larger quartz sand grains show strain shadows, thus suggesting that some of them were derived from metamorphic rocks. Of the unstrained grains, most appear to have come from granites or other igneous rocks, but some are probably from quartz veins and some from quartzites. A small percentage of chert grains may have come either from cherty limestone or from cherts associated with basic lavas.

Frosting on sand grains is generally attributed to transportation by wind rather than water. The implication, therefore, is that much or all of the quartz sand in the Greenbrier formation was wind-transported. This does not necessarily mean that the clastic beds in the Greenbrier are dune deposits, although some may be, because the frosting may be inherited from an earlier cycle of erosion, transportation, and deposition. Further, there is an alternative explanation for some frosting in the Greenbrier. On some grains the frosted surface reflects tiny sparkles of light, suggesting that the frosting may have been caused after deposition in the limestone either by deposition of drusy secondary quartz or by the etching of polished sand grains. If so, the frosting has no significance in regard to wind or water transportation prior to deposition of the quartz sand. At some places in the Greenbrier the alternative explanation is not feasible, because the larger grains are frosted but the smaller grains are not. In etching or deposition of secondary quartz, all grains should be affected.

HEAVY MINERALS

The Greenbrier formation contains small amounts of tourmaline, zircon, and other mineral grains of relatively high specific gravity. In the Appalachian basin such heavy minerals have been exceedingly useful in determining the sources of the sediments. To study these heavy minerals, the carbonate in samples of the Greenbrier was digested in hot hydrochloric acid, the residual sand was sieved, and the light and heavy minerals in the $\frac{1}{8} - \frac{1}{16}$ mm. size grade were separated in acetylene tetrabromide (specific gravity 2.93). In the heavy-mineral separates so obtained, tourmaline and zircon are the dominant minerals. Garnet, staurolite, red and yellow rutile, barite, chromite, and black opaque grains (probably ilmenite) are present in smaller amounts. Pyrite is very abundant in some samples. Altered grains and some rock fragments are present in all samples.

As in most other sands of the Appalachian basin, the relative proportion of different heavy minerals or different varieties of the same mineral has little significance. In contrast, the roundness of tourmaline and zircon grains is highly significant. Roundness refers to the curvature of corners and edges, and is independent of the general shape of the grain. Roundness, as used by the writer in Appalachian basin studies has been discussed elsewhere.[8]

[8] Gordon Rittenhouse, "Grain Roundness—a Valuable Geologic Tool," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 30 (1946), pp 1192–97.

———, "Analytical Methods as Applied in Petrographic Investigations of Appalachian Basin," *U. S. Geol. Survey Circ. 22* (1948), p. 20.

The roundness of tourmaline and zircon grains has been determined for samples of the Greenbrier from 21 wells and 4 outcrop localities as listed in Table I and shown in Figure 5. On the basis of tourmaline and zircon roundness, deposits of the Greenbrier may be divided into three areas (Fig. 5). In area I, which includes Pennsylvania and part of northern West Virginia, about 8 per cent of the tourmalines are round, 83 per cent are subangular, and 9 per cent are angular. In area II, which includes most of western and northwestern West Virginia, the tourmalines average 27 per cent round, 69 per cent subangular, and 4 per cent

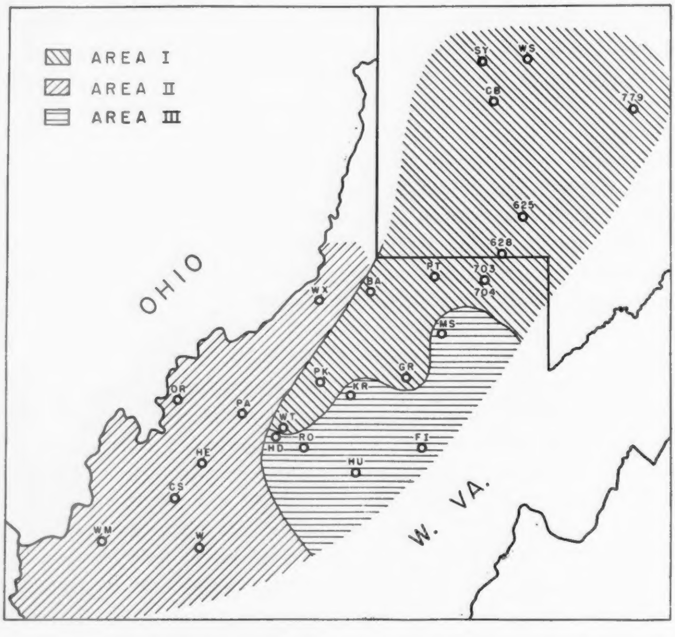

FIG. 5.—Map showing areas in which rounding of tourmaline and zircon grains in Greenbrier formation differs (see text and Table II) and showing location of samples used in heavy-mineral investigations. Letter symbols at locations of wells correspond with those shown in Table I.

angular. When the tourmaline roundness of samples from these two areas are plotted on a triangular diagram (Fig. 6), the data from the two areas fall into different parts of the diagram. Zircon grains from areas I and II also differ in roundness. That differences of the magnitude shown in Figure 6 could be due to chance is almost impossible.

In area III, the roundness of tourmalines and zircons of some samples is similar to that of area I; of others, to that of area II. In the samples from some wells this relation is clear; in others it is not. In the Roberts well (RO) (Fig. 4), for

example, three samples from the third clastic zone are of the area II type, and two samples of the fourth clastic zone are of area I type. In the Patterson well (PA) (Fig. 4), which is in area II, the samples are from the basal (third) clastic zone and are of the area II type. In the South Penn Natural Gas Company's A. & N. Hardman well No. 1 (HD), which is halfway between the Roberts and Patterson wells, the uppermost sample is of area II type, and the two lower samples are similar to those in area I. In A. D. Prunty's O. C. and W. H. Hutchinson well No. 1 (HU) midway between the Patterson No. 1 (PA) and the Hoover

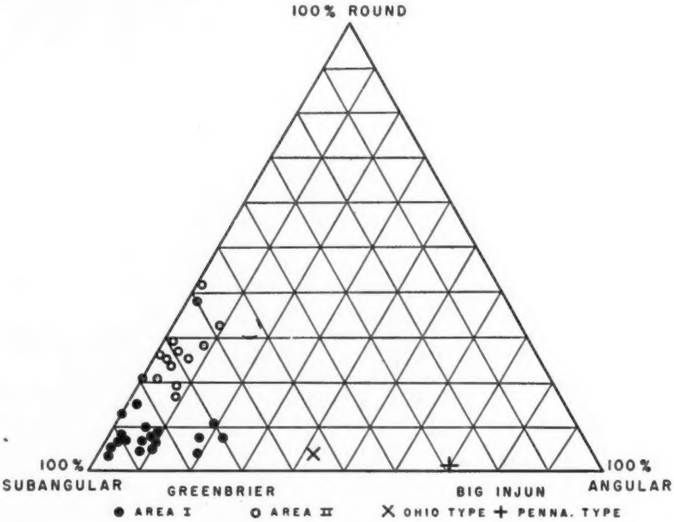

FIG. 6.—Triangular diagram showing relative roundness of tourmaline grains from $\frac{1}{8}$ to $\frac{1}{16}$ mm diameter in Greenbrier formation.

and Davis No. 1 (HO) (Fig. 4), the single sample is of area II type and is from a zone that appears to be correlative with the third clastic zone in the Patterson well.

In the southern part of area III the evidence seems clear that tourmaline and zircon roundness differ in the third and fourth clastic zones. The third zone is an eastward extension of area II; the fourth zone is a southward extension of area I. Farther north and east the relations in area III are not as clear. Both area I and area II types of roundness are present in different zones, but their relation to the various clastic beds can not be determined exactly and may be more complex than it is farther south. More insoluble-residue and heavy-mineral studies are necessary in the northern and eastern part of area III.

Figure 7 shows the area in which the third and fourth clastic zones are thick-

est. Because the samples are widely scattered, the boundaries of these two zones are only approximate. South and east of the limits shown in Figure 7 both zones are thinner and contain less quartz sand.

Although two types of tourmaline and zircon roundness occur in the Greenbrier, both types are characterized by the small percentage of angular grains.

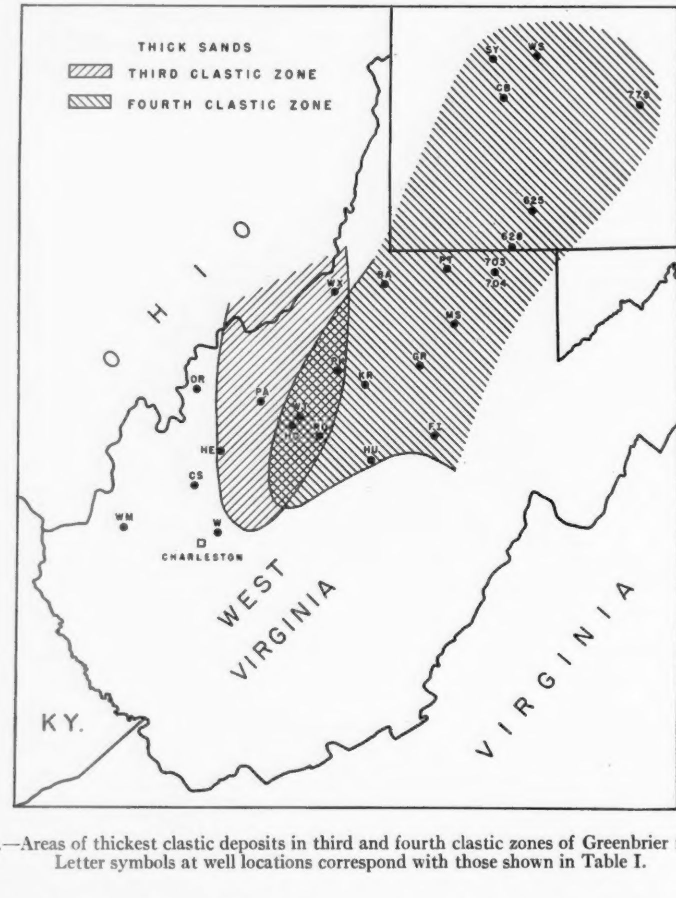

FIG. 7.—Areas of thickest clastic deposits in third and fourth clastic zones of Greenbrier formation Letter symbols at well locations correspond with those shown in Table I.

Also, both types are characterized by tourmalines of which 35 per cent are brown, 50 per cent are green, and 15 per cent are of other colors. Both roundness and color are useful criteria by which to determine whether the Greenbrier was derived from pre-existing sediments or from the same sources as a pre-existing sediment of the Appalachian basin.

The evidence now available indicates that no large part of the quartz sand in the Greenbrier formation was derived from the Big Injun sand even though the Big Injun was the surface formation over which the Greenbrier sea or ocean transgressed during middle or late middle Greenbrier time.

The Big Injun sand is of two petrographic types, namely, (1) an "Ohio type" that occurs in Ohio and extends eastward 15–40 miles into West Virginia and western Pennsylvania, and (2) a "Pennsylvania type" that occurs in Pennsylvania and northern West Virginia. In color of tourmalines these two types of Big Injun are very similar, each having approximately 40 per cent of brown tourmalines, 44 per cent green, and 16 per cent of other colors. The difference between the two petrographic types is in the roundness of the tourmalines and zircons. In the Ohio type, 4 per cent of the tourmaline is round, 54 per cent is subangular, and 42 per cent is angular. In the Pennsylvania type, 1 per cent is round, 29 per cent is subangular, and 70 per cent is angular. The average roundness of tourmaline in the two types of Big Injun sand is shown in Figure 6.

TABLE II

PERCENTAGE OF ROUND, SUBANGULAR, AND ANGULAR GRAINS OF TOURMALINE $\frac{1}{8}$–$\frac{1}{16}$-MILLIMETER DIAMETER IN GREENBRIER FORMATION, BIG INJUN SAND, AND SANDS OF POTTSVILLE FORMATION

Occurrence	*Round*	*Subangular*	*Angular*
Greenbrier formation—Area I	8	83	9
Area II	27	69	4
Big Injun sand—Ohio type	4	54	42
Pennsylvania type	1	29	70
Pottsville formation—Sharon conglomerate	22	40	38
Olean conglomerate	1	26	73

The color of the tourmalines in the Greenbrier formation and the Big Injun sand is very similar. On the basis of color the Greenbrier might have been derived from the Big Injun, or from the same sources as the Big Injun.

In the roundness of tourmalines and zircons, however, the two formations differ. The tourmaline and zircon grains in the Greenbrier are more rounded (Table II) and, as the Greenbrier is the younger formation, the question is whether the difference in roundness can reasonably be attributed to wear that occurred after the sand was eroded from the Big Injun and before it was redeposited in the Greenbrier. Some consideration of the processes by which grains are rounded and also of the method of measuring roundness is needed to answer this question. In this investigation, grains that showed no wear of the corners and edges were classed as angular. Grains that showed some wear, even though the rounding was slight, were classed as subangular. Consequently, a small amount of abrasion might change many grains from angular to subangular. Such change when plotted on a triangular diagram like Figure 6 would move the average roundness markedly away from the angular corner toward the subangular corner

of the diagram. The change from 70 or 42 per cent angular grains in the Big Injun to 9 per cent angular grains in the Greenbrier of area I (Table II) probably would not occur in the local reworking of Big Injun sand, but might occur during one cycle of erosion, transportation, and deposition if the transportation was prolonged.

The change from subangular to round involves much more wear from the corners and edges of the grains and would take many times as much transportation as the change from angular to subangular. Tumbling-barrel experiments[9] indicate that for grains between 1 and 0.5 mm. in diameter such change will not occur in less than 5,000 miles of transportation. The much smaller grains studied in this investigation would have required transportation much farther for this change to occur.

If the Big Injun was the source of the sand in the Greenbrier of area II, however, the airline distance from the place of erosion to the place of deposition must have been only a few hundred miles. This fact eliminates rivers and the wind as possible transporting agents. Along beaches, however, sand is moved many feet toward and away from the beach for every foot of alongshore movement. Consequently, sand grains might travel thousands of miles in being moved an airline distance of a few hundred miles.

Under such conditions, however, the sand should become progressively more rounded away from its source. But no such progressive change in roundness occurs in the sand in the Greenbrier of area II. Therefore, sand of the Greenbrier of area II can not be reworked by Big Injun sand. The conclusion from the heavy-mineral studies is that the Greenbrier and Big Injun may have been derived from the same ultimate source, but that the immediate sources of the Greenbrier probably were sediments that had passed through several more cycles of erosion, transportation, and deposition than the sediments that provided the sand for the Big Injun.

The Squaw sands of Pennsylvania, West Virginia, and Ohio, and the Weir sand of West Virginia below the Big Injun are very similar to the Big Injun in both color of tourmalines and in roundness of tourmalines and zircons. Consequently, the arguments advanced against the Big Injun as the immediate source of the quartz sand in the Greenbrier apply in equal degree to them.

The Berea and the Upper Devonian sands are probably not important sources for the quartz sand of the Greenbrier. Although the tourmaline and zircon roundness of some of these deposits is similar to that of the Greenbrier, small but significant differences are present in the relative proportion of the several varieties of tourmaline. In the Greenbrier, approximately 35 per cent of the tourmaline is brown. In the Berea and Upper Devonian sands, only 22 per cent of the tourmaline is brown. This is a significant difference. The quartz sand in the

[9] G. A. Thiel, "The Relative Resistance to Abrasion of Mineral Grains of Sand Size," *Jour. Sed. Petrology*, Vol. 10 (1940), pp. 103–24.

Greenbrier could have been derived only in part from the Berea or Upper Devonian sands, or from the same sources as these sands.

The heavy-mineral data can be used also to differentiate the sands of the Greenbrier from those of the Pottsville above and the Big Injun or the Keener sand below. Where the basal Greenbrier contains much quartz sand, or where the upper part of the Greenbrier has been removed by erosion and sands of the Pottsville lie on the sandy basal phase of the Greenbrier, the contacts between the several formations may be difficult to recognize. This difficulty is illustrated by the drillers' misidentification of the sandy basal phase of the Greenbrier as Big Injun or Squaw sand in much of West Virginia.

In many places the quartz sand in the Greenbrier is rounded and frosted whereas that of the Pottsville and Lower Mississippian is angular to subangular and is not frosted. In such places the sands of the Greenbrier may be easily differentiated from the others by examination with a hand lens or binocular microscope. Elsewhere the difference in roundness of the heavy minerals as shown in Table II is the only criterion known to the writer by which the sands can be differentiated.

DEPOSITIONAL HISTORY OF GREENBRIER FORMATION

LIMESTONE BEDS

The Greenbrier formation is only one of a series of formations that was deposited during a period in which the locus of deposition in the Appalachian basin was shifting. To obtain a clear picture of its origin, the place of the Greenbrier in that period must be considered.

During late Devonian time, the greatest thickness of sediment was deposited along a northeast-southwest-trending axis in eastern and southeastern West Virginia.[10] Subsidence of the Appalachian geosyncline must have been more rapid here than elsewhere on the northwest. In very late Devonian time the rate of subsidence along this axis decreased and probably some uplift occurred. By Berea time, the center of the basin of active subaqueous deposition had shifted into southeastern Ohio, and most of West Virginia was a low land area that sloped gently west or northwest.[11] This shift in axis was accompanied or closely followed by a change in the source of sediment, as indicated by the presence of more angular sand, and by a change in the proportion of the tourmaline varieties in sands above the Berea. Northern and northeastern areas replaced eastern areas as the source of most Appalachian basin sediments during Mississippian and early Pennsylvanian time.

[10] H. P. Woodward, "Devonian System of West Virginia," *West Virginia Geol. Survey*, Vol. 15 (1943), p. 532.

[11] Gordon Rittenhouse, "The Distribution of Several Types of Berea Sand in West Virginia, Eastern Ohio, and Western Pennsylvania," *U. S. Geol. Survey Prelim. Map 58*, Oil and Gas Investig. Ser. (1946).

During most of Pocono time the major area of deposition was in Ohio, western Pennsylvania, and western West Virginia. During this period minor transgressions of the sea eastward over the land permitted accumulation of some sediments in central and western West Virginia. Some of the sediments in this area may well be continental in origin. After deposition of the Big Injun sand, which was confined to Ohio, western Pennsylvania, and western and northern West Virginia, the red Maccrady shale was spread as a veneer over southeastern Ohio and southern West Virginia. The distribution of the Maccrady indicates a shifting of the depositional axis from Ohio eastward into West Virginia.

The oldest Greenbrier sediments occur in southeastern West Virginia. This fact indicates that the axis of thickest sediment accumulation had completed its shift to southeastern West Virginia and that subsidence was again dominant in this area. In southeastern West Virginia, the deposition of 1,000 feet of Greenbrier was followed by deposition of 3,400 feet of Mauch Chunk, and 3,800 feet of Pottsville sediments.

As nearly as it can be reconstructed from the evidence now available, the history of the Greenbrier is as follows. The earliest accumulation took place along the margin of an ocean or in a shallow epicontinental sea in southeastern West Virginia. Whether the place of accumulation was a sea or an ocean is not known, as no conclusive evidence is available to prove or disprove the existence of a landmass that would have formed the southeastward margin of the epicontinental sea. The sea, if it existed, may have been a northeastern extension of a larger sea in eastern Kentucky.

At and near the northwest shore of the sea or ocean, clastic deposits composed dominantly of lime sand and oölites accumulated in beach, bar, channel, and perhaps dune deposits. Some of the material may have been swept many miles seaward across the shallow bottom to form a rather extensive sheet of clastic material. Beyond the clastic deposits, fine-grained limestones showing indistinct or no clastic texture were deposited. Perhaps they were chemical precipitates, but probably most of them were composed of silty débris which was derived from the zone of abrasion near the shore and was carried farther into the basin than the coarser material.

The lime sand and oölites were formed locally where waves and currents were active, and were mixed with a small amount of quartz sand that was brought into the area of deposition from a distant source. Because the percentage of quartz sand would decrease away from the immediate source, and such decrease in the Greenbrier appears to be from northwest to southeast, the quartz sand in the Greenbrier probably was derived from the north or northwest. Whether this sand was brought across a low, flat land area by sluggish streams, or was moved southward along the shore of the sea or ocean is not known. If the source was from the northwest, the quartz sand in the earliest Greenbrier may show petrographic similarity to the Ohio type Big Injun; if from the north, to the Pennsylvania type Big Injun, or to the quartz sands of the Greenbrier in northern West Vir-

ginia. Petrographic studies necessary to determine the source of the early sands of the Greenbrier can not be made until adequate samples are available.

After Greenbrier deposition was started, subsidence tended to enlarge and deepen the area of accumulation, and sedimentation to fill it. Probably neither process proceeded at a uniform rate. During periods when subsidence slightly exceeded the rate of deposition, the beach line advanced slowly on the land area, and a continuous layer of nearshore clastic limestone was deposited. During periods of alternate rapid and slow sedimentation or subsidence, discontinuous series of parallel nearshore deposits accumulated. They were probably similar in shape and extent although not in composition to the deposits along the present Atlantic Coast or to some of the shoestring sands of Kansas.

When the rate of sedimentation exceeded that of subsidence, the sediments encroached upon the sea and the zone of clastic sediments migrated into the basin across the indistinctly clastic or non-clastic lime beds. Each advance and retreat of the sea produced a clastic non-clastic couplet. At least nine and perhaps as many as thirteen major advances and retreats occurred during Greenbrier time. Data now available are insufficient to outline accurately the extent of each clastic zone, or to show the location of the shoestring clastic deposits.

During the periods when the third and fourth clastic zones were deposited, much more quartz sand was brought to the area of accumulation than at other times. The general pattern of quartz sand distribution and the mineralogy of the deposits indicate that the quartz sand was derived from older Paleozoic sediments on the north or northeast and the north or northwest. The pattern suggests southward transportation of the quartz sand by waves and currents along an oscillating beach or a broad, shallow submerged ridge. Whether the smaller amount of quartz sand in the first and second clastic zones is the result of the source of the quartz sand being cut off, or to transgression of the sea (and the clastic deposits) northwestward beyond the present limits of the Greenbrier is only conjectural.

As already noted, the sections at the Maud Sommerville No. 1 (S) and Addison 10a (AI) wells have uncertain significance. If the basal beds of the Greenbrier in these wells are fourth clastic zone or older, part of the Greenbrier must have accumulated in a secondary basin of deposition. This subsidiary basin, northwest of the main area of Greenbrier accumulation, would have been separated from it by a broad, low ridge somewhat west of the present Warfield anticline.

If the basal beds in the Sommerville and Addison wells are correlative with the third clastic zone, the broad low submerged ridge along which sand was brought from the north may have existed, but there would have been only one sea, although a deeper part of the basin of accumulation may have been present on the northwest. If all of the Greenbrier in the Sommerville and Addison wells is younger than the third clastic zone, neither a ridge nor a secondary basin would have been present. Further information that would show which of these three

possibilities is correct would clarify our knowledge of the history of structural deformation in the Appalachian basin and perhaps give clues helpful in explaining the distribution of later Paleozoic sediments in this area.

DOLOMITE AND DOLOMITIC LIMESTONE

As half of the oil and gas produced from the Greenbrier formation is from dolomite or dolomitic limestone, an understanding of how these rocks formed would be helpful in locating and extending new fields and in planning secondary-recovery operations. The present investigation does not solve the problem of how the dolomite formed. It does eliminate direct precipitation of dolomite from sea water as a method by which most of the dolomite was formed and suggests four ways in which the magnesium-bearing waters may have been introduced into the limestone of the Greenbrier subsequent to its deposition.

Dolomite and dolomitic limestone are widely but not uniformly distributed in the Greenbrier formation. Most dolomite occurs in the basal 5–30 feet of the section. Much dolomitic limestone also is in this basal part, but some occurs higher in the formation, generally in beds 30 feet thick or less. Areally the basal part of the Greenbrier may change from dolomite to dolomitic limestone or limestone in a few miles. Both the position of dolomite and dolomitic limestone at the base of the formation and their non-uniform distribution must be considered in explaining their origin.

The dolomite is commonly light brown to almost white and has a characteristic sugary texture. It is ordinarily composed of rhombs of dolomite of coarse silt size and generally contains scattered grains of rounded and frosted quartz sand. In the Addison well 10a (AI), the upper few feet of the basal dolomite zone contains irregular cavities 1 by $\frac{1}{2}$ by $\frac{1}{4}$ inch in maximum dimensions. These cavities are lined with calcite rhombs 1/16 mm. in diameter and pyrite crystals of smaller size. In cuttings from other wells, open pores $\frac{1}{8}$ mm. or less in diameter were observed. Both the characteristic association of the quartz sand with the dolomite and the presence of cavities in the dolomite from the Addison well 10a are considered significant in explaining the origin of the dolomite.

The dolomitic limestones show all gradations from limestone to dolomite. The sugary texture that is characteristic of dolomite is partly developed in the dolomitic limestone and most of the dolomitic limestones contain some quartz sand. Much of the dolomitic limestone is fine-grained and has no obvious clastic texture; some is definitely clastic. The dolomitic limestones of clastic texture show all stages of dolomitization from initial filling of pores between lime sand and oölite grains, through progressive obliteration of the clastic texture by growth of tiny dolomite rhombs.[12] The dolomitization is a secondary-replacement process. Martens and Hoskins[13] also believe that most of the dolomite is secondary.

Throughout the Greenbrier formation clastic limestones are composed of

[12] In some almost completely dolomitized limestones, the original clastic texture can be brought out by etching with dilute hydrochloric acid.

[13] J. H. C. Martens, and H. A. Hoskins, "Dolomite Zone at Base of Greenbrier Limestone (Big Lime)," *West Virginia Geol. Survey Rept. Investig. 4*, p. 7.

lime sand, oölites, and quartz sand in various proportions. Quartz sand does not occur in limestones with no obvious clastic texture, unless the limestone is dolomitic. In some of the dolomitic limestone that contains quartz sand, the secondary development of the dolomite can be demonstrated. The conclusion is that all or nearly all of the dolomites and dolomitic limestones that contain

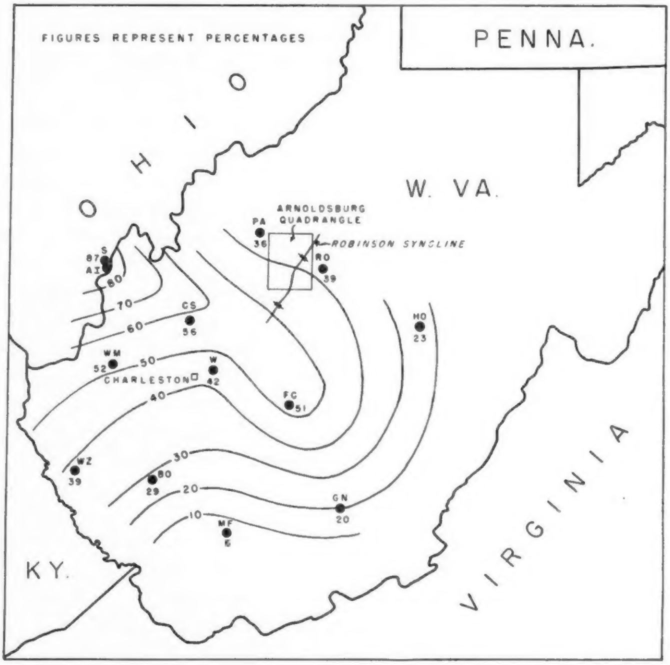

FIG. 8.—Map showing percentage of Greenbrier formation that is dolomite or dolomitic limestone. Letter symbols at well locations correspond with those shown in Table I.

quartz sand were originally clastic limestones composed of lime sand, oölites, and quartz sand.

In some wells in southern West Virginia, some anhydrite is associated with the dolomite. In this area part of the dolomite may be a primary chemical precipitate.

From the writer's examinations of samples of the Greenbrier section in eleven wells in central and southern West Virginia and one well in Ohio, the percentage of dolomite and dolomitic limestone in each well was computed.[14] These percentages were plotted in Figure 8, and lines showing equal dolomite and dolomitic

[14] Some limestone classed as dolomitic contains lime sand and oölites. Because such limestone was considered dolomitic in preparing Figure 8, and as containing lime sand and oölites in preparing Figure 3, the percentages of lime sand, oölites, and dolomitic limestone total more than 100 for some wells.

limestone content were drawn. The dolomitization has followed a definite regional pattern. The dolomitization pattern differs from the patterns of quartz sand and oölite and lime sand distribution of Figures 2 and 3. It also deviates from that of the regional structure.

The distribution of dolomite and dolomitic limestone shown by Figure 8 is influenced in part by the increase in the total thickness of the Greenbrier on the

FIG. 9.—Map showing thickness, in feet, of dolomite and dolomitic limestone in Greenbrier formation. Letter symbols at well locations correspond with those shown in Table I.

southeast. Plotting the total thickness rather than the percentage of dolomite and dolomitic limestone beds yields a different pattern. As shown in Figure 9, the total thickness of dolomitic beds is least along a north-south axis through west-central West Virginia. East and west the total thickness is greater. This distribution of dolomitic beds transects the regional structure, and the original distribution of quartz sand, oölites, and lime sand. Too much weight should not be given to the data on which Figures 8 and 9 are based, as they are scattered and may not give a true picture.

In the southern two-thirds of the Arnoldsburg Quadrangle (Fig. 8) studies of

samples by Martens and structure mapping on the base of the Greenbrier limestone suggest a close relationship between structure and dolomitization. In this area almost all production of oil and gas is from the basal part of the Greenbrier (fourth clastic zone). In the Robinson syncline (Fig. 8) this basal 20–40 feet of the Greenbrier formation is dolomite or dolomite and dolomitic limestone. On the flanks of the syncline, where gas occurs, only dolomitic limestones are recorded. In the Arnoldsburg Quadrangle insufficient data are available to prove the exclusive dependence of dolomitization on structure. In fact, variations in thickness of dolomite from well to well in the syncline suggest the alternate possibility that only part of a larger pattern of dolomitization has been revealed by the samples now available. Because the dolomite and dolomitic limestone are confined to the basal 20–40 feet of the formation in most places it seems improbable that dolomitization could have been controlled by migration of magnesium-bearing solutions upward along vertical fractures. Landes[15] has suggested such an origin for dolomite in the Trenton limestone of some parts of Michigan, Indiana, and Ohio.

The incomplete data now at hand suggest that dolomitization of the Greenbrier may have occurred in several ways.

1. As the dolomite is secondary and has replaced original clastic limestone, much magnesium must have been introduced into the Greenbrier sediments after their deposition. Most of the dolomite is in a basal zone 30 feet or less in thickness and this zone transgresses sedimentary units. This fact suggests a close relationship between dolomitization and the underlying rocks. Reaction between the basal limestone and magnesium-bearing waters squeezed out of the underlying beds during their compaction seems possible. Structural movements, by hastening the compaction or by providing pathways for migration of the solutions, might have concentrated the accumulation of dolomite in some synclines.

2. Another possibility is that dolomitization occurred during the periods of regression that followed accumulation of the basal clastic deposits at each locality. During exposure of the limestone above sea-level, solution above the ground-water table could produce pores and cavities of the kind found in the Addison well 10a. Below the ground-water table, magnesium-charged ground water moving from the non-calcareous sediments farther north or west might dolomitize the limestones. During the next transgression, calcite and pyrite might be deposited in the cavities. Under these conditions the pattern of dolomite replacement might be locally irregular, especially if the ground-water movement was controlled by varying porosity of the clastic limestones or by pre-existing drainage ways over which the Greenbrier was deposited.

3. Magnesium also might have been introduced from the south or southeast. Magnesium-bearing waters squeezed out of the sediments by compaction or structural movements may have migrated updip through the more porous basal clastic

[15] Kenneth K. Landes, "Porosity through Dolomitization," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 30 (1946), p. 317.

deposits of the Greenbrier. Replacement, perhaps due to relief of pressure, would occur in the basal clastic zone but not to any great extent in the eastward-extending clastic wedges higher in the formation. Irregular areal distribution of the dolomite and dolomitic limestone would result from differences in original porosity in the basal clastic limestones.

4. Another method of introducing magnesium is possible. This involves downward circulation of sea water through the clastic limestones as they were accumulating. Replacement of calcite by dolomite would occur below the active surface of sediment accumulation. Because the eastward-extending wedges of clastic limestone have not been dolomitized, this type of replacement, if it occurred, must have been restricted to nearshore localities during the first transgression of the Greenbrier seas across a non-calcareous land area. Under these conditions, belts of dolomite and dolomitic limestones parallel with the shorelines would be expected. The pattern within the belts would probably be somewhat irregular due to differing porosity of the clastic limestones and variation in the conditions of the water above them.

How may future work help to prove which of these methods or which combination of methods actually occurred in the Greenbrier? First, a more detailed study is needed to determine the pattern of dolomite occurrence and its relation to original conditions of deposition, structure, and production. This study should cover one or more counties in which many samples are available. Second, careful petrographic examinations, particularly of intraformational breccias and conglomerates, may help to determine when the dolomite replacements occurred. Some core samples from the Greenbrier would be especially helpful in such studies.

PRODUCTION OF OIL AND GAS

Martens' sample log data indicate that approximately half of the Greenbrier production of oil and gas is from the basal dolomite and dolomitic limestone zone and half is from clastic limestone beds. Only a few of the wells produce from indistinctly clastic or non-clastic limestone. Although the few hundred wells studied by Martens may not be strictly representative of the Greenbrier as a whole, the relative magnitude of production from the various types is probably of the right order. If so, the implications are of great importance in exploration, development, and secondary recovery.

As pointed out earlier in this paper, the clastic limestone beds were formed as nearshore deposits in a sea that was alternately transgressing and regressing. The mixtures of lime sand, oölites, and quartz sand were deposited in the same way as nearshore deposits of pure quartz sand. They represent beach, bar, dune, and channel deposits. The beach, bar, and dune deposits should be long, relatively narrow accumulations, approximately parallel with the shoreline. The channel deposits should also be long and narrow, but approximately at right angles to the shore, and at slightly greater depths than the associated beaches, bars, and dunes.

The clastic limestone beds are approximately wedge-shaped with their thicker parts on the northwest, but locally considerable variation in thickness should occur. At times when rates of sedimentation and subsidence were almost in balance, shorelines would be stable, and well developed, relatively thick near-shore deposits would accumulate. A change in the relative rates, followed by rapid shift of the shoreline northwestward (and possibly southeastward) would leave these deposits almost isolated, as shoestring type lenses of clastic sediment. In such deposits structure would be of secondary importance in localizing the accumulations of oil and gas.

In contrast, during periods of slow, uniform transgression or regression of the sea, blanket deposits of clastic limestones would accumulate. In these more uniform deposits, oil and gas accumulations should show more structural control than in the shoestring type of deposits. Even in the blanket clastics, however, local variations in original porosity, commonly parallel with the shoreline, would control some oil and gas accumulation.

The exact trend of the ancient Greenbrier shorelines has not been determined. In general the trend in northern and central West Virginia probably is slightly north of northeast-southwest; in southern West Virginia, it is more nearly northeast-southwest.

The quartz sand in the Greenbrier apparently migrated southwestward along the shorelines. This fact would indicate an effective wind from the east or northeast. Along the present Atlantic Coast and in the shoestring sands of Kansas,[16] bars are offset slightly when broken by tidal inlets. The direction of offset is controlled by wind direction. Where offsets occur in the Greenbrier, each bar should be offset west of the adjacent one on the north.

Production from the clastic limestone should be localized where the clastic beds are best developed, namely, toward the northwest margin of each clastic zone. Toward southeastern West Virginia, production may be expected from progressively lower strata. The data suggest that these lower zones may be much narrower than the upper ones which are best developed farther northwest.

During Greenbrier time, repeated transgressions and regressions of the sea occurred. Some of the regressions may have been caused by uplift rather than by filling of an intermittently subsiding basin with sediments. If so, the limestones of the newly emergent land area would have been subjected to leaching and solution. As a result, highly porous zones of relatively wide but irregular lateral extent and limited vertical extent may have been developed. Such zones in the Greenbrier may be reservoirs for oil and gas. Dolomitization may or may not have been associated with such regressions.

At present not all the processes or combinations of processes that have controlled dolomitization in the Greenbrier are known. Consequently, the shapes

[16] N. Wood Bass, "Origin of the Shoestring Sands of Greenwood and Butler Counties, Kansas," *Kansas Geol. Survey Bull. 23* (1936).

and trends of the dolomite zones can not be predicted, although some possibilities may be outlined.

First, most known dolomitization in the Greenbrier is in the basal 30 feet or less of the formation. In future exploration throughout West Virginia, particular attention should be given to this basal zone as a possible producing zone.

Second, data now available for southeastern West Virginia suggest that less dolomite and dolomitic limestone occur in Boone, Wyoming, and McDowell counties than in the counties on the east and west.

Third, most of the dolomite is secondary and probably the magnesium necessary for its formation was brought into the Greenbrier. Because zones of original porosity would offer easiest passage to magnesium-bearing solutions, original conditions of deposition probably partly controlled the later dolomitization.

If migration of magnesium-bearing solutions was generally from southeast to northwest or the reverse, the dolomite zones may have northeast-southwest extensions or offsets where the migrating solutions crossed original porous zones.

Fourth, in spite of much evidence that dolomitization is partly controlled by original conditions of deposition, structural control may be very important. In one locality dolomitization seems to be most extensive in the synclines. If this holds true for other areas, oil should occur in dolomites in the synclines and gas in dolomitic limestones on the flanks.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1731-1746, 4 FIGS., 1 TABLE

MAYFIELD POOL, CUYAHOGA COUNTY, OHIO[1]

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ABSTRACT

The Mayfield pool, the most productive of the Newburg-sand gas pools in Ohio, is in northeastern Cuyahoga County. The rocks that have been tested by drilling range in age from Upper Ordovician to Upper Devonian. Rocks that crop out in the area are Upper Devonian and Mississippian in age. They are extensively covered by Pleistocene and Recent deposits. Gas and a small amount of oil are produced from the Newburg sand (Middle Silurian) at an average depth of 2,875 feet, and from the so-called Oriskany sand (Lower Devonian) at a depth of 1,800 feet. The reservoir is of the structural type in the Oriskany sand and is of a combined structural and porosity type in the Newburg sand.

The structure has not been completely outlined because of the cover of Pleistocene deposits at the surface and restrictions on drilling south and southwest of the pool. However, at the surface the structure appears to resemble a dome with limbs dipping about 0°18′. In the subsurface the structure appears to be a broad anticline trending northeast with a known closure of approximately 100 feet and with its southeast limb dipping 0°38′. Fifty-two tests, eleven of which were dry holes, have been drilled on the anticline. The total yield of gas, on January 1, 1949, has been nearly 14½ billion cubic feet from wells having a distribution ratio of 30 acres per well. The chances of obtaining oil or gas from deeper Ordovician and older strata are considered to be chiefly dependent on the amount of closure in the structure in these deeper strata, and on the porosity of the rocks.

LOCATION AND TOPOGRAPHY

The Mayfield pool, which has yielded more gas from the so-called Newburg sand than any other pool in Ohio, is in northeastern Cuyahoga County, 16 miles east-northeast of Cleveland's Public Square. Drilling has been confined to the villages of Mayfield and Highland Heights (Fig. 1), but it would undoubtedly be extended southward into adjoining villages if restrictions against it were lifted.

The pool is 6 miles south of Lake Erie in an area of rolling highlands which are a part of the Appalachian Plateau. The plateau in the vicinity of the pool has a maximum altitude of approximately 1,050 feet. Its northern boundary is an irregular declivity called the Portage escarpment. North of this escarpment lie remnants of glacial lake beds that constitute the Erie plain and form the shore of Lake Erie whose mean altitude is 573 feet. The other boundaries of the plateau are outside the area covered by this paper. The plateau is deeply dissected by the broad valley of the Cuyahoga River, 13 miles southwest of the gas field, and by the steep-walled valley of the Chagrin River, 2 miles east of the field. Tributaries of these rivers and smaller streams that flow directly into the lake have cut short, steep-sided valleys into the periphery of the plateau.

[1] Read before the Association at Pittsburgh, October 5, 1948. Manuscript received, May 15, 1949. Published by permission of the director of the United States Geological Survey.

[2] Geologist, United States Geological Survey. The geology of the Mayfield area was mapped by the writer acting as an independent geologist in the fall of 1933. Altitudes of outcrops and outlying wells were determined by the use of two surveying altimeters, whose readings were checked with altitudes shown on the topographic map as often as required by weather conditions. Readings were repeated whenever necessary to insure accuracy within a range of 5 feet. Altitudes of the wells in the pool, supplied by the Benedum-Trees Oil Company, were determined by spirit-level surveys.

Acknowledgment of aid in the preparation of this paper is tendered officials of the Benedum-Trees Oil Company who supplied drilling and production data and gave permission to use them in this paper. John H. Melvin, State geologist of Ohio, and his staff also furnished helpful data.

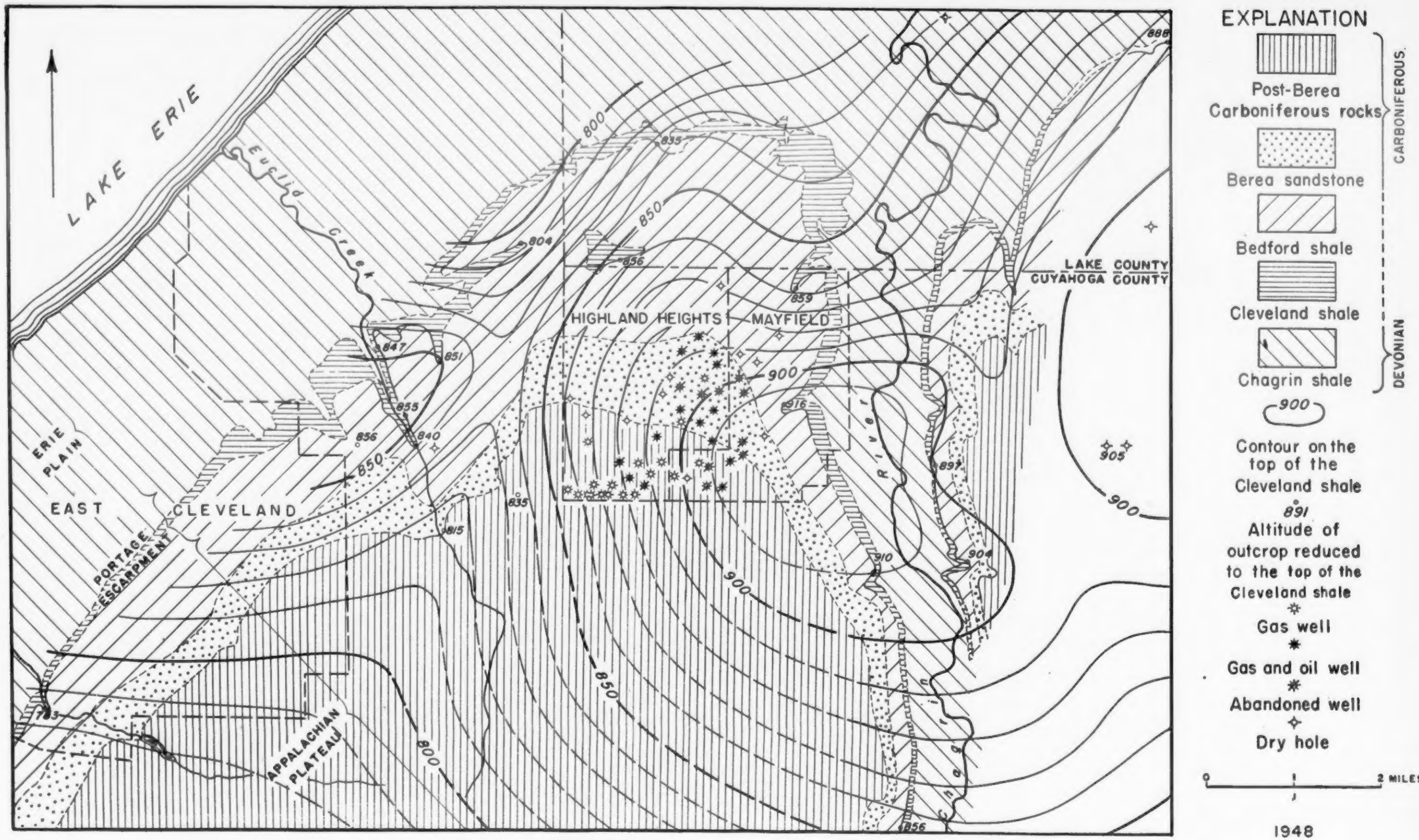


FIG. 1.—Geologic map of parts of Cuyahoga and Lake counties, Ohio, showing distribution and structure of Paleozoic rocks.

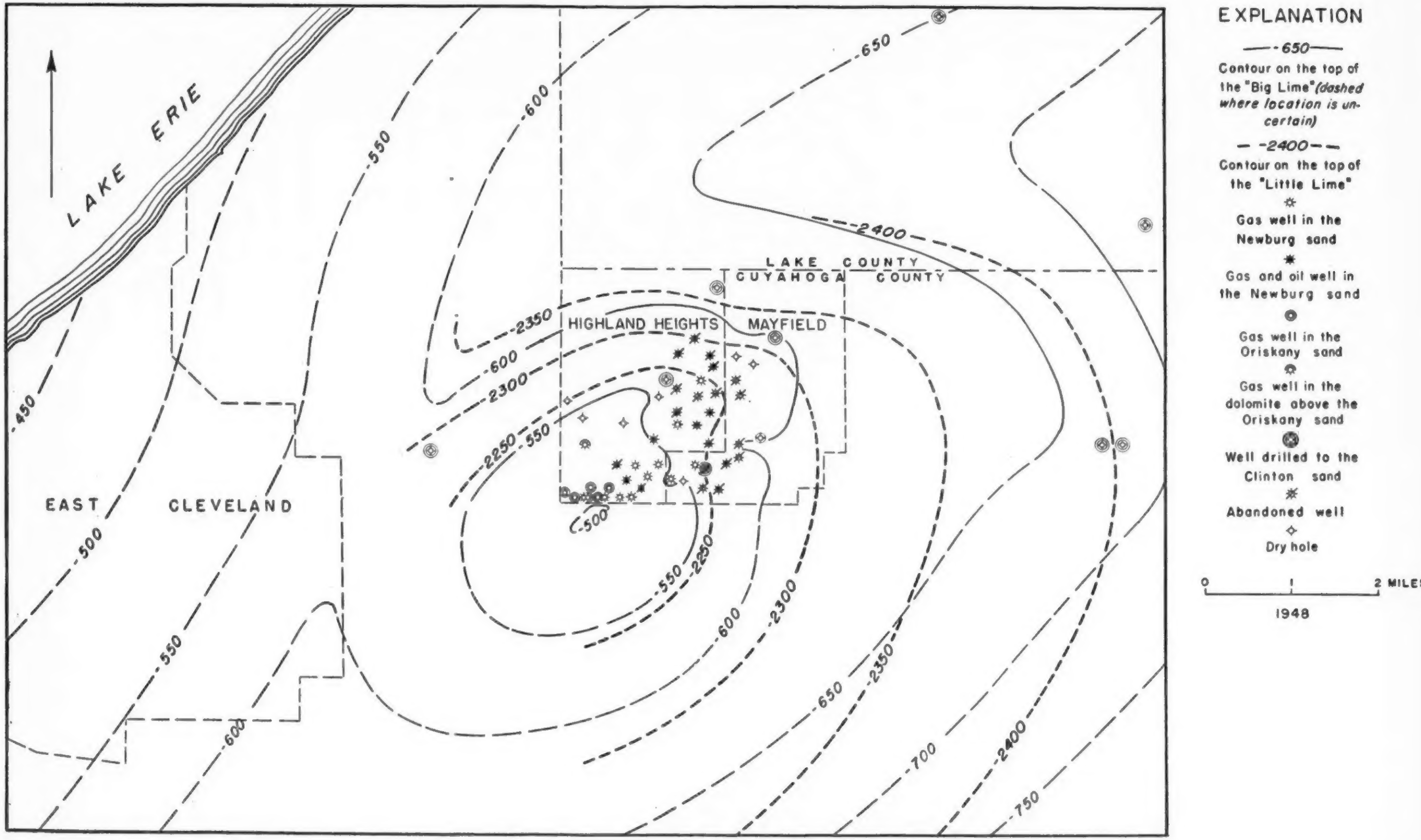


FIG. 2.—Subsurface structure map of parts of Cuyahoga and Lake counties, Ohio.

Geology

SUBSURFACE ROCKS

The subsurface rocks of the Mayfield area that have been tested by drilling range from the Upper Ordovician red Queenston shale to the Upper Devonian Chagrin shale. Near the bottom of this sequence are sandstones, known by the

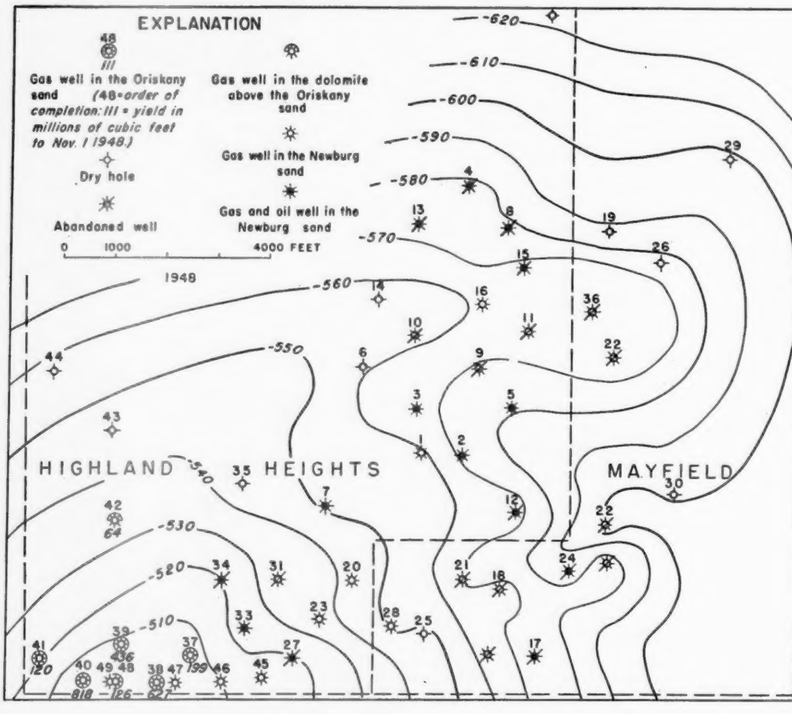


FIG. 3.—Subsurface map of Mayfield pool showing structure of top of "Big lime" and yield from wells in Oriskany sand.

drillers as the Clinton sands, which in some localities are gas-bearing. Nearly 100 feet above the top of the Clinton sand sequence is the base of the unit known to drillers as the "Big lime," a sequence of dolomite and limestone 1,600 feet thick that contains some beds of salt, anhydrite, and shale. Within the "Big lime" there are two zones from which commercial quantities of gas and oil have been obtained. They are known to drillers as (1) the Newburg sand, which is in the lower part of the "Big lime" and is a zone in the Niagara dolomite, and (2) the Oriskany sand (Lower Devonian), which is in its upper part. The "Big lime" in-

cludes in ascending order the following formations: Niagara dolomite, Salina formation, Bass Island dolomite, Oriskany(?) sandstone, Detroit River dolomite, and the Columbus and Delaware limestones. Overlying the "Big lime" is a sequence of gray, brown, and black Devonian shale approximately 1,450 feet thick.

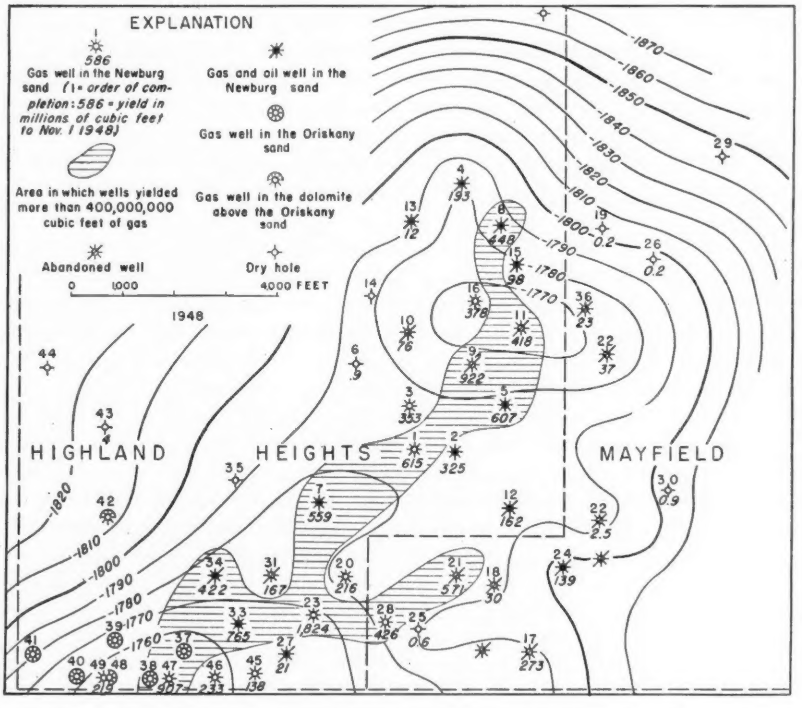


FIG. 4.—Subsurface map of Mayfield pool showing structure of top of anhydrite and yield from wells in Newburg sand.

Ordovician Rocks

The Ordovician rocks that have been tested by drilling in the Mayfield pool consist of the upper part of the Upper Ordovician Queenston shale. Two wells, No. 14 (Whitbeck) and No. 29 (Greenwood) (Figs. 3 and 4), penetrated 512 feet and 444 feet, respectively, of this formation which in this area consists chiefly of grayish red to dusky red slightly calcareous claystone that includes brownish gray to medium-gray calcareous claystone and siltstone in its lower half. This part of the sequence also contains 10–20 per cent of finely crystalline limestone and dense silty limestone and dolomite.

Silurian Rocks

The subsurface rocks assigned to the Silurian are divided in ascending order into (1) a basal sequence of shale containing the Clinton sands in its lower part and a single bed of limestone near its top, (2) the Niagara dolomite (Middle Silurian), and (3) the rocks of Cayugan (Upper Silurian) age.

BASAL SEQUENCE

In the area of the Mayfield pool the lithologic units of the basal sequence are variable in number and of irregular thickness, but generally include in ascending order: three beds of shale separated by two sandstones, called by drillers the Clinton sands; a limestone 10–40 feet thick, called locally the "Little lime," that is useful in this locality for determining the structure of the older Silurian rocks; and a shale 75 feet thick, that separates the underlying "Little lime" from the overlying sequence known as the "Big lime."

Clinton sands.—The Clinton sands in the basal sequence have not been productive thus far in the Mayfield pool, though one or more of them have yielded gas in the Cleveland pool (developed about 1914), in the Canton gas pool of fairly recent discovery, and in scattered wells chiefly in the Erie plain. Here as elsewhere in northeastern Ohio the Clinton sands contain no free water. They occur as lenticular bodies interbedded with claystone in a stratigraphic interval of 155 feet and are thickest in its upper part. They are composed chiefly of very fine-grained angular equi-dimensional clear quartz grains with scattered grains of milky quartz and heavy minerals. Some beds are so well cemented by silica as to be semi-quartzitic; others contain large proportions of interstitial hematite, and some show traces of calcareous cement. On the whole, they appear under the microscope to have very low porosity. As Clinton sand characteristics seem to remain most uniform in north-south trends, the fineness of grain size and the high degree of cementation of the Clinton sequence at Mayfield will discourage prospecting to this horizon for a considerable distance north and south of the pool.

NIAGARA DOLOMITE

Overlying the basal sequence is the Niagara dolomite, the bottom unit of the sequence known by drillers as the "Big lime." The Niagara is fine- to coarse-grained gray or light brown dolomite 500 feet thick. Approximately 135 feet below its top is a bed of anhydrite that ranges in thickness from 5 to 15 feet. This bed, called the "Oyster shell" because the drill cuttings from it resemble fragments of shell, is an excellent marker for the Newburg sand, the top of which generally is 30 feet below the "Oyster shell."

Newburg sand.—The so-called Newburg sand is medium- to coarse-grained porous dolomite and is not composed of quartz grains as its name suggests. It occurs in one or more lenses of irregular thickness in a zone as much as 125 feet thick. The top of the sand is 6–42 feet below the "Oyster shell," the marker bed that is 135 feet below the top of the Niagara. In some of the wells this zone con-

sists of three lenses separated by partings of dense dolomite. The average thickness of these subdivisions, from the anhydrite downward, in seventeen wells is as follows: anhydrite, 10 feet; dense dolomite, 10 feet; first porous zone, 32 feet; dense dolomite, 5 feet; second porous zone, 30 feet; dense dolomite, 15 feet; third porous zone, 30 feet.

The porosity of nine specimens of the producing sand, as determined by microscopic examination of polished sections, ranged from 5 to 37 per cent and averaged 14 per cent. The porosity is related to grain size, being greater in coarse-grained than in fine-grained dolomite. The cavities are vug-like and owe their present shape to solution of the dolomite. The factors that control the distribution of the cavities were not discovered but the occurrence of the cavities more plentifully in coarse-grained dolomite than in fine-grained dolomite suggests that intercrystalline voids were influential in distributing fluids that dissolved the dolomite and formed the cavities.

Porosity in the Newburg sand is general throughout northeastern Ohio and is effective in permitting circulation of fluids, as shown by the strong flow of salt water that is ordinarily encountered in it. However, effective porosity or permeability in the Mayfield pool is locally very irregular.

ROCKS OF CAYUGAN AGE

The rocks of Cayugan age consist of the Salina formation and the overlying Bass Island dolomite. The Salina formation is divisible into two parts: the lower part, approximately 260 feet thick, is composed of shale, salt, and dolomite; the upper part, averaging 130 feet thick, consists chiefly of salt. The Bass Island dolomite is brown and gray dolomite 350 feet thick.

DEVONIAN ROCKS

Lower, Middle, and Upper Devonian rocks are represented in the subsurface. The Lower Devonian epoch is represented by the Oriskany(?) sandstone; the Middle Devonian consists in ascending order of the Detroit River dolomite and the Columbus and Delaware limestones.[3] The Upper Devonian rocks of the subsurface include the shales called Huron by Newberry,[4] and part of the overlying Chagrin shale.

LOWER DEVONIAN ROCKS

Oriskany(?) sandstone.—The Oriskany(?) sandstone, called Oriskany sand by drillers, occurs throughout the area but is irregular in thickness, ranging from 10 to 79 feet and averaging 32 feet. It consists chiefly of rounded to subangular clear quartz grains 0.2–0.4 mm. in diameter. Larger and smaller frosted grains are scattered sparingly through it and are preponderant close to its top. The grains are cemented with silica but form a friable, porous mass. The sandstone is re-

[3] J. F. Pepper, "Areal Extent and Thickness of the Salt Deposits of Ohio," *Ohio Jour. Sci.*, Vol. 47, No. 6 (1947), p. 227.

[4] J. S. Newberry, *Ohio Geol. Survey Rept. Prog.* (1869), p. 18.

corded in nearly all of the wells in northeastern Ohio that are deep enough to penetrate it, and correlation of the records indicates that it is the Austinburg sand of the Austinburg, Saybrook, and Eaglesville gas pools in Ashtabula County, 35 miles northeast of Mayfield. A strong flow of brine is obtained from all of these wells, indicating that the sandstone has a high degree of permeability.

MIDDLE DEVONIAN ROCKS

The Middle Devonian rocks which in this area consist of chert and cherty dolomite 340 feet thick were not divided by the writer into their component formations, the Detroit River dolomite and Columbus and Delaware limestones.

UPPER DEVONIAN ROCKS

Huron shale.—The Upper Devonian rocks are composed almost entirely of shale 1,450 feet thick. The lower 560 feet of this shale is equivalent to that called Huron by Newberry.[5] Later writers, however, are not in accord regarding its name or age equivalents. Cushing,[6] describing the Cleveland district, said that these shales are Portage in age. He found them overlying light gray calcareous shale of Hamilton age, 60 feet thick. He also believed that the shales are older than the Huron shale which does not extend to the Cleveland area. Chadwick[7] assigned them to the Chemung group, which in New York overlies rocks of Portage age. No evidence was obtained in the Mayfield area to resolve these differences; the lower 560 feet of the Upper Devonian rocks in the Mayfield area, however, consists in ascending order of brown or dark gray shale 60 feet thick, predominantly very light gray shale 240 feet thick, and brown or dark gray shale 260 feet thick.

Chagrin shale.—The Chagrin shale, shown by well records to have a total thickness of 900 feet in the Mayfield area, overlies the brown and gray shales of controversial age. As much as 300 feet of the upper part of the formation is exposed in the mapped area. Because the formation is uniform in character, the description of its exposed part may be representative of the entire formation.

EXPOSED ROCKS

The rocks that crop out in the vicinity of the Mayfield pool belong to the Devonian and Carboniferous systems of the Paleozoic era and to the Pleistocene and Recent series of the Quaternary system. The Paleozoic rocks are exposed chiefly where streams have cut through the Pleistocene deposits. The outcrops of the older rocks, therefore, occur in a relatively narrow belt on three sides of the gas pool. On the east they crop out rather continuously in the bluffs of the

[5] J. S. Newberry, *op. cit.*

[6] H. P. Cushing, Frank Leverett, and Frank R. Van Horn, "Geology and Mineral Resources of the Cleveland District, Ohio," *U. S. Geol. Survey Bull. 818* (1931), p. 32.

[7] George H. Chadwick, "Great Catskill Delta, and Revision of Late Devonic Succession, Revised Correlations," *Pan-Amer. Geol.*, Vol. 60, No. 4 (1933), pp. 280–81.

Chagrin River. On the north they are exposed discontinuously in the steep-sided valleys of the streams that cut the Portage escarpment. On the west they are sparingly exposed in the headwaters of the tributaries of the Cuyahoga River. Pleistocene sediments consisting of glacial drift form a covering of irregular thickness on the Appalachian plateau. Beach sand and lake clay, deposited by the Pleistocene lakes Maumee, Whittlesey, Warren, and Lundy, glacial predecessors of Lake Erie,[8] cover most of the Portage escarpment and Erie plain. Recent deposits include alluvium on the flood plains of the streams, and beach sand along the shore of Lake Erie. The distribution of the Paleozoic rocks, from which the Quaternary sediments are considered to have been removed, is shown in Figure 1.

Devonian Rocks

UPPER DEVONIAN ROCKS

Chagrin shale.—The Chagrin shale (Upper Devonian) forms the lower parts of the valley walls and underlies the Erie plain at a shallow depth. It consists chiefly of soft, light-colored, bluish gray or greenish gray claystone. Thin calcareous siltstone flags of the same color occur at random intervals and in discontinuous sheets. They are more plentiful in the upper than in the lower part of the exposed Chagrin shale. Their superior resistance to erosion causes them to stand out in prominent relief on the furrowed slopes of the claystone and is responsible for many small water-falls in the streams. The siltstone flags are useful indicators of dip in an otherwise homogeneous sequence but they lack the continuity or distinctive characteristics that would permit correlation beyond a single exposure.

Small flat claystone concretions, generally with a ferruginous nucleus, are common along some bedding planes.

The top of the Chagrin shale has been eroded by planation to form a slightly uneven surface, a disconformity that is not readily detected because outcrops generally are scattered. The most obvious evidence of this disconformity is the variable thickness of the overlying Cleveland shale, the top of which is an uneroded surface.

Of the 900 feet of Chagrin shale in this area nearly 300 feet are exposed. The formation thickens eastward in the northeastern part of Ohio, from 500 feet at Cleveland to at least 1,200 feet along the eastern boundary of the state.[9]

Devonian or Carboniferous Rocks

The age of the Cleveland shale, which overlies the Chagrin shale, and of the still younger Bedford shale is controversial. Faunal and facies aspects suggest Devonian age to some geologists and Carboniferous age to others. The United States Geological Survey currently classifies these formations as Devonian or Carboniferous.

[8] H. P. Cushing *et al.*, *op. cit.*, pp. 96–99.

[9] H. P. Cushing *et al.*, *op. cit.*, pp. 33 and 35.

Cleveland shale.—The Cleveland shale was deposited on the slightly uneven surface of the Chagrin shale. The magnitude of this disconformity is indicated by the range from 25 to 54 feet in the thickness of the Cleveland shale. The disconformity is marked in many places by a thin layer of yellow-weathering mudstone overlain by dark mudstone that contains much marcasite. The thickness of these mudstones ranges from a fraction of an inch to several inches. The remainder of the formation is fissile black claystone that breaks into small blocky laths. The black claystone forms precipitous, hackly-faced, overhanging slopes that generally are in marked contrast to the more gently sloping, smoothly furrowed surfaces of the Chagrin shale.

Bedford shale.—The Bedford shale lies conformably on the Cleveland shale. The Bedford, which has an average total thickness of 80 feet, consists chiefly of red, brown, or gray claystone, but at its base in the northwestern part of the area there is a sandy member called the Euclid sandstone lentil. The lentil is generally 25 feet thick and consists of alternating beds of gray claystone and fine-grained, bluish gray sandstone. Pyrite-bearing concretions as much as 2 inches in diameter occur in its lower part. The sandstones thicken toward the top of the lentil and the claystones thin to mere partings. In the vicinity of Euclid Creek in the northwestern part of the area, the lentil is 40 feet thick, the increase in thickness being in the upper sandstone which has been quarried for building stone known as bluestone. Channels cut by streams into the upper part of the Bedford shale during early Berea time increase the variation in thickness introduced by the Euclid lentil. The regional stratigraphic relations of the Bedford shale have recently been discussed by de Witt.[10]

Carboniferous Rocks

The rocks definitely assigned to the Carboniferous system are the Berea sandstone and Orangeville shale of Mississippian age. Younger Mississippian and Pennsylvanian rocks crop out in near-by areas but in the vicinity of Mayfield they have been covered by Pleistocene deposits or were extensively removed by ice planation during Pleistocene time.

Berea sandstone.—The Berea sandstone overlies the Bedford shale disconformably, filling channels in the shale and forming a massive sequence above it. The Berea is light gray to light brown sandstone and is specked with pyrite that forms dark brown spots on weathering. Beds several feet thick occur in the lower part but in the upper part the beds are thin and some of them are separated by claystone partings. Cross lamination and ripple marks a few inches in amplitude are common features. The sandstone is composed of medium-sized, subangular, clear, glittering quartz grains, that are only moderately well cemented. The formation is generally 50 feet thick, but where it has filled channels in the Bed-

[10] Wallace de Witt Jr., "The Stratigraphic Relationship of the Berea, Corry and Cussewago Sandstones in Northeastern Ohio and Northwestern Pennsylvania," *U. S. Geol. Survey Chart 21*, Oil and Gas Investig. Ser. (1946).

ford shale it is considerably thicker. The regional relationships of these sand-filled channels have recently been discussed in the series of studies of the Berea sand by J. F. Pepper and his associates,[11] particularly in their map which includes the Mayfield area.

Orangeville shale.—The Orangeville shale lies without angular discordance above the Berea sandstone. It crops out in scattered localities, at which only the lower part of the formation is generally exposed. The formation consists chiefly of soft, homogeneous, light-colored, bluish gray to bluish black claystone, much of which resembles the Chagrin shale excepting for the absence of concretions and flagstones. The Orangeville shale is most extensively exposed in Euclid Creek where it is nearly 125 feet thick.

The base of the Orangeville shale is marked in places by pyritiferous sandstone or mudstone a few inches thick. Above this pyritiferous layer is bluish black claystone, the stratigraphic position of which corresponds with that of the Sunbury shale. This claystone thickens northeastward, ranging from 6 feet thick near Bedford, 11 miles south of Mayfield, to 30 feet thick on the East Branch of the Chagrin River, 10 miles northeast of Bedford. Overlying this shale is thin-bedded siltstone with interbedded, fine-grained, light gray sandstone which is 8 feet thick. It is called the Aurora sandstone by Cushing[12] and the Chardon sandstone by Prosser.[13]

SURFACE STRUCTURE

The Mayfield pool is on the east flank of the Cincinnati arch, which in this locality dips southeastward. The critical dip of a structural trap for oil and gas in this area, therefore, is northwest.

The surface structure of the Paleozoic rocks in the Mayfield area was mapped on the top of the Cleveland shale. The structure could not be completely delineated because of the absence of diagnostic outcrops south and southwest of the pool. Outcrops elsewhere, however, show that the pool is on the northwest flank of a dome-like structure which has 70 feet of closure on the west and at least 100 feet on the north (Fig. 1). The crest of this structure is near the southeast corner of Mayfield. From this locality the shale dips north and west at an average rate of 27 feet per mile or at an angle of 0° 18′. The southeastward dip is slightly less but it continues with but minor interruptions for several miles. A low saddle occurs east of the dome and separates it from a broad terrace beyond. The dip southwest is highly conjectural because of the absence of outcrops.

Gas and minor quantities of oil occur on the northwest and west flank of the structure represented by contours on the top of the Cleveland shale (Fig. 1), on the part of the structure opposite to that where accumulation due to migration

[11] J. F. Pepper *et al.*, "Map of the Berea Sand of Northern Ohio," *U. S. Geol. Survey Map 39*, Oil and Gas Investig. Ser. (1945).

[12] H. P. Cushing *et al.*, *op. cit.*, p. 50.

[13] C. S. Prosser, *Ohio Geol. Survey Bull. 15*, 4th Ser. (1912), pp. 219, 229.

up the regional dip would be expected. The apparent anomaly arises from the fact that the crests of the subsurface structures, wherein the gas and oil occur, are approximately $2\frac{1}{2}$ miles west of the crest of the structure of the Cleveland shale (Fig. 2). This difference of position is caused by the thickening of the strata between the top of the Cleveland shale and the top of the "Big lime" in a relatively short distance. As a result of this thickening, the divergence between these horizons is at the rate of 35 feet per mile east-southeastward. If this divergence is graphically applied to the structure of the top of the Cleveland shale, the position of the structure of the top of the "Big lime" can be approximately duplicated. This procedure was used to locate the first well and was sufficiently accurate to place it in the productive area of the pool.

SUBSURFACE STRUCTURE

The top of the "Big lime" was selected as the most practicable subsurface horizon for contouring because it is easily recognized by drillers, its depth generally is accurately determined, and in this locality the configuration of its top, except for minor irregularities, is representative of the structure of its older components (Figs. 3 and 4).

Contours on the top of the "Big lime" show that the subsurface counterpart of the dome-like surface structure is a broad anticline, the major axis of which trends northeastward (Fig. 2.) Its actual shape, however, is not known because of restrictions on drilling in the area south and southwest of the pool. The wells that have been drilled show critical closures on the west and north of at least 76 feet and 120 feet, respectively (Fig. 2). The southeast limb of the anticline dips $0° 38'$.

The structure shown by the top of the "Big lime" persists downward at least 1,700 feet to the "Little lime," which is a short distance above the Clinton sands. Five wells drilled to the Clinton sands on the flanks of the anticline, and four others east and northeast of it, indicate that the dip of the "Little lime" on the west, north, and east sides of the anticline is slightly greater than that on the top of the "Big lime" (Fig. 2). A well in Solon Township, Summit County, 10 miles south of the pool, suggests that the dip of the two subsurface horizons is approximately the same in this direction. The steepening of the structure of the deeper rocks in the vicinity of the pool suggests that the anticline continues as a prominent structure to greater depths.

History of Development[13a]

The geologic work that led to the development of the field was done by the writer, as an independent geologist, in the fall of 1933. The difficult task of as-

[13a] *Editor's note.*—Since this paper was written, the Benedum-Trees Oil Company drilled a sub-Trenton test at a site 1,000 feet north of well No. 38 (Figs. 3 and 4). The test was drilled to the total depth of 5,823 feet, or 843 feet below the top of the Trenton limestone. About 100,000 cubic feet of sweet gas and a showing of oil came from fine-grained dolomitic sand at 5,690–5,692 feet and from sandy dolomite at 5,692–5,707 feet. An increase in oil came from dolomitic sand at 5,715–5,717 feet.

sembling a solid block of leases from small holdings was accomplished by Harry B. Zahniser, on behalf of the Benedum-Trees Oil Company.

The first well drilled in the area, the Straight No. 1, was completed, June 29, 1938, in the Newburg sand, at the depth of 2,806 feet. Twenty-six wells were completed during the next 18 months. Thereafter, development of the pool continued more slowly until fifty-two wells had been drilled. Ten of these were dry holes or yielded inconsequential amounts of gas. By January, 1949, 10½ years after discovery of the pool, eighteen wells, including the discovery well, were still active.

GAS YIELD AND FACTORS AFFECTING IT

During the early period of development of the pool, most of its site was laid out for suburban settlement, but only a few buildings, other than those belonging to small farms, had been erected. Subsequently, however, many residences were built and several installations catering to the public, such as golf courses and riding clubs, were established in the area. These added greatly to the problems of field development.

Gas Yield from Mayfield Pool, Cuyahoga County, Ohio*

Year	*Annual Yield in Thousands of Cubic Feet*		
	Newburg Sand	*Oriskany Sand*	*Total*
1938–1939	1,629,914		1,629,914
1940	2,504,394		2,504,394
1941	1,643,388	4,914	1,648,302
1942	1,076,533	623,743	1,700,276
1943	1,072,281	811,273	1,883,554
1944	698,393	354,081	1,052,474
1945	583,604	262,512	846,116
1946	834,468	177,709	1,012,177
1947	1,018,637	168,986	1,187,623
1948	832,041	73,330	905,371
Total	11,893,653	2,476,548	14,370,201

* Data furnished by the Benedum-Trees Oil Company. A small amount of gas in addition to that shown in the table was obtained from two wells offsetting the Benedum-Trees property.
Several of the wells in the Newburg sand yielded a small amount of oil, which by the end of 1948, aggregated approximately 20,000 barrels.

The total yield of gas to January 1, 1949, was nearly 14½ billion cubic feet of gas, 82 per cent of which came from the Newburg sand, and the remainder from the Oriskany sand. The accompanying table shows the annual yield from each of these sands.

The principal productive wells, of which there were forty-two, are in an area

The strata in these intervals, when treated with acid, yielded 10 barrels of Pennsylvania grade oil and 10 barrels of salt water per day. The oil decreased during subsequent testing, and thereafter the hole was deepened. At 5,763–5,765 feet a showing of dark oil was found in sandy dolomite, and at 5,823 feet the hole filled 4,000 feet with salt water. Paleontologic criteria for determining the age of the gas- and oil-bearing strata are not available but the limestone immediately above 5,713 feet is reported to resemble lithologically limestones of Black River age.

of 1,200 acres. From these figures the well-distribution ratio is seen to be approximately 30 acres per well. This low ratio is due in part to a few twin wells but chiefly to the small sizes of the individual holdings and the difficulty of unitizing these tracts.

There can be little doubt that this closely spaced pattern has resulted in a larger yield. For instance, if a normal gas-well spacing had been used, well No. 28, in the southwest corner of Mayfield between dry hole No. 25 and the relatively small well No. 20 (Fig. 4), would not have been completed. Similarly, well No. 47 on the south line of Highland Heights probably would have been located farther west, outside the best part of the pool, if wider spacing had been used. The yield from adjoining wells suggests that little of the gas from wells 28 and 47 would have been recovered through their offsets.

Gas Yield from Newburg Sand

The total yield from wells in the Newburg sand has differed widely, ranging from a few thousand cubic feet to 1,824,000,000 cubic feet. Furthermore, the distribution of large and small wells in the better parts of the pool is not regular, as shown by wells 15, 27, and 31 in Highland Heights, and 18 and 25 in Mayfield, which have much lower yields than adjacent wells (Fig. 4). This suggests that the gas yield of some of the wells is only slightly affected by their offsets.

Gas has been obtained from each of the three zones in the Newburg sand but it is most commonly found in the upper zone. In some of the wells the first and second zones are gas-bearing, but in none of them are all three productive. Gas is obtained from the third zone only in wells on the highest part of the structure. The average initial natural yield from each of the zones was nearly equal, being approximately 500,000 cubic feet per day in the better part of the pool. The initial rock pressure was 1,100 pounds. Salt water with a very high brine content is generally associated with the gas in small or large amounts and eventually drowns out the well.

The writer believes that the gas and oil in the Newburg sand of the Mayfield pool were gathered by circulating solutions from possibly widespread sources and trapped in the anticlinal structure. Evidence of a relatively free circulation of fluids in the sand in this part of Ohio is shown by the strong flow of water commonly found in wells that drill through it. A widespread occurrence of source materials is indicated by the showings of oil and gas recorded in most of these wells. The importance of structure in the formation of the reservoir is shown by (1) the concentration of gas along the anticlinal axis and on the southeast (basinward) limb of the structure (Fig. 4); (2) the tendency of wells low on the structure to be drowned by water before those at higher structural locations are seriously affected; and (3) the absence of commercial quantities of gas or oil in most of the Newburg sand wells in northeastern Ohio that are located unfavorably with regard to structure.

Although structure appears to be chiefly responsible for the accumulation of the gas and oil that form the Mayfield pool, porosity of the sand controls the yield in the pool. This is shown by the irregular distribution of large and small wells. For instance, well No. 23 in the southeast corner of Highland Heights (Fig. 4) yielded 1,755,000,000 cubic feet of gas, but its southwest offset, No. 27, higher on the structure, yielded only 21,000,000 cubic feet. Other examples of irregularity of yield can be noted in the figure.

The irregularities in porosity may not be entirely random. The largest wells occur in a narrow crooked belt along the crest of the anticline (Fig. 4). Wells northwest of this belt were small or non-productive, although some of them are as favorably situated on the structure as the larger ones. This linear arrangement of areas of high porosity may be explained by a concentration of fractures, such as develop along the axes of folds. Such fractures would facilitate the circulation of the fluids that dissolved the dolomite and formed the cavities. If this hypothesis is accepted, we must conclude that exceedingly gentle flexing of massive rock sequences may produce joint patterns of importance to the accumulation of gas and oil.

Gas Yield from Oriskany Sand

Gas is obtained from the so-called Oriskany sand through six wells near the top of the structure. All of these wells are at or above the −520-foot contour on the top of the "Big lime." Wells at greater depths have yielded only brine from this sand (Fig. 3). The gas accumulated in the top few feet of sand, which in most wells is penetrated only 2 or 3 feet to avoid the water below. The wells are relatively uniform in yield, ranging from 111 to 818 million cubic feet for the period ending December 31, 1947. These conditions indicate that the effective porosity of the Oriskany sand is uniform and that structure controls accumulation.

The initial rock pressure in the gas reservoir of the Oriskany was 650 pounds per square inch.

DRILLING PRACTICE

The wells were drilled with cable tools. The average drilling time to the Oriskany sand was 23 days and to the Newburg sand, 44 days. The average well to the Newburg sand used a conductor 80 feet long, 2,100 feet of $8\frac{1}{4}$-inch casing to shut off the water in the Oriskany sand, and 2,875 feet of 3- or $4\frac{1}{2}$-inch tubing set on a packer which was placed 4 joints above the bottom. One or two perforated joints were used below the packer. The average well to the Oriskany sand required the conductor and 1,900 feet of tubing.

The Newburg sand was generally treated with one or more charges of acid of 1,000–1,500 gallons each. Larger or smaller charges were used in a few instances. The records of twenty-four treated wells indicate that the yield was not appreciably increased in three wells but that in the remainder the average increase over the initial yield was 217 per cent.

Possibilities

There is little chance of extending the productive area of either the Oriskany or the Newburg sand unless drilling restrictions are removed from the lands south and southwest of the drilled area.

Under present conditions new reserves of gas and oil must be sought in the deeper rocks. The chance of finding gas in the Clinton sands appears remote because of the several unsuccessful tests to that zone, and the impervious character of the Clinton beds.

The possibility of obtaining gas or oil in the rocks of Trenton (Ordovician) and pre-Trenton (Ordovician and Cambrian?) age is problematic. The Trenton rocks have been commercially productive in Ohio only in the Lima-Findlay field, high on the axis of the Cincinnati arch. They may, however, yield commercial quantities of oil or gas on the flanks of the arch if a structural trap with large closure or an adequate stratigraphic or textural trap is found.

Rocks of pre-Trenton age, chiefly those near the base of the Ordovician, may also be productive under these conditions. The small wells at Tiffin, Caledonia, Pickerington, and Newark, 100–120 miles southwest of Mayfield, are encouragingly significant in appraising these possibilities. These wells are on the east flank of the Cincinnati arch 1,000–2,500 feet structurally below its crest.[14] They yielded oil or gas from sandy beds thought to be below the unconformity at the base of the Ordovician.[15]

The Mayfield anticline is the largest subsidiary structure in northeastern Ohio known to the writer. Whether the closure of the anticline is sufficient to form a reservoir in the rocks of Trenton and pre-Trenton age, however, can not be forecast, nor can the operator be sure that the conditions that caused the favorable porosity in the Newburg sand also affected the deeper beds.

[14] Charles R. Fettke, "Subsurface Trenton and Sub-Trenton Rocks in Ohio, New York, Pennsylvania, and West Virginia," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 8 (1948), Fig. 1.

[15] *Ibid.*, p. 1491.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1747-1766, 7 FIGS.

GEOLOGIC IMPLICATIONS OF AEROMAGNETIC SURVEY OF CLEARFIELD-PHILIPSBURG AREA, PENNSYLVANIA[1]

H. R. JOESTING,[2] FRED KELLER, JR.,[2] AND ELIZABETH KING[2]
Washington, D. C.

ABSTRACT

An aeromagnetic survey was made in November, 1946, of a 1,785-square-mile area in central Pennsylvania, to gain information on the pre-Cambrian basement rocks and their relation to structure in the overlying Paleozoic sedimentary rocks. The area surveyed lies mainly in the Allegheny Plateau, but also includes a small part of the Valley and Ridge Province.

The major magnetic features are believed to reflect inhomogeneities in a geologically complex basement, rather than irregularities of the basement surface. Analysis of the magnetic results also indicates that the basement structural trends diverge somewhat from surface structure; and that the basement surface is not deformed concordantly with the highly folded Paleozoic rocks in the Valley and Ridge part of the area.

Depth estimates place the basement 19,000–22,000 feet beneath the surface in the west-central part of the area, which is in good agreement with estimates based on geologic considerations. Magnetic evidence, admittedly inconclusive, indicates that the basement may be deeper southeast of the Appalachian Front, rather than northwest, as is generally supposed.

INTRODUCTION

An aeromagnetic survey of part of central Pennsylvania was made in November, 1946, to gain information on the pre-Cambrian basement rocks, including their composition, structure, approximate depth, and relation to the geologic structure of the overlying sedimentary rocks.

A total of 1,785 square miles was covered by the aeromagnetic survey, in an area approximately 34 miles north-south and 52 miles east-west. The area includes most of Clearfield County, the western half of Centre County, and small parts of the adjoining counties on the north (Fig. 1).

FLIGHT AND COMPILATION PROCEDURES[3]

As shown on the aeromagnetic map (Fig. 1), north-south lines were flown at ½-mile intervals, approximately 1,000 feet above the surface. The north-south

[1] Read before the Association at Pittsburgh, October 5, 1948. Manuscript received, March 11, 1949. Published by permission of the director of the United States Geological Survey.

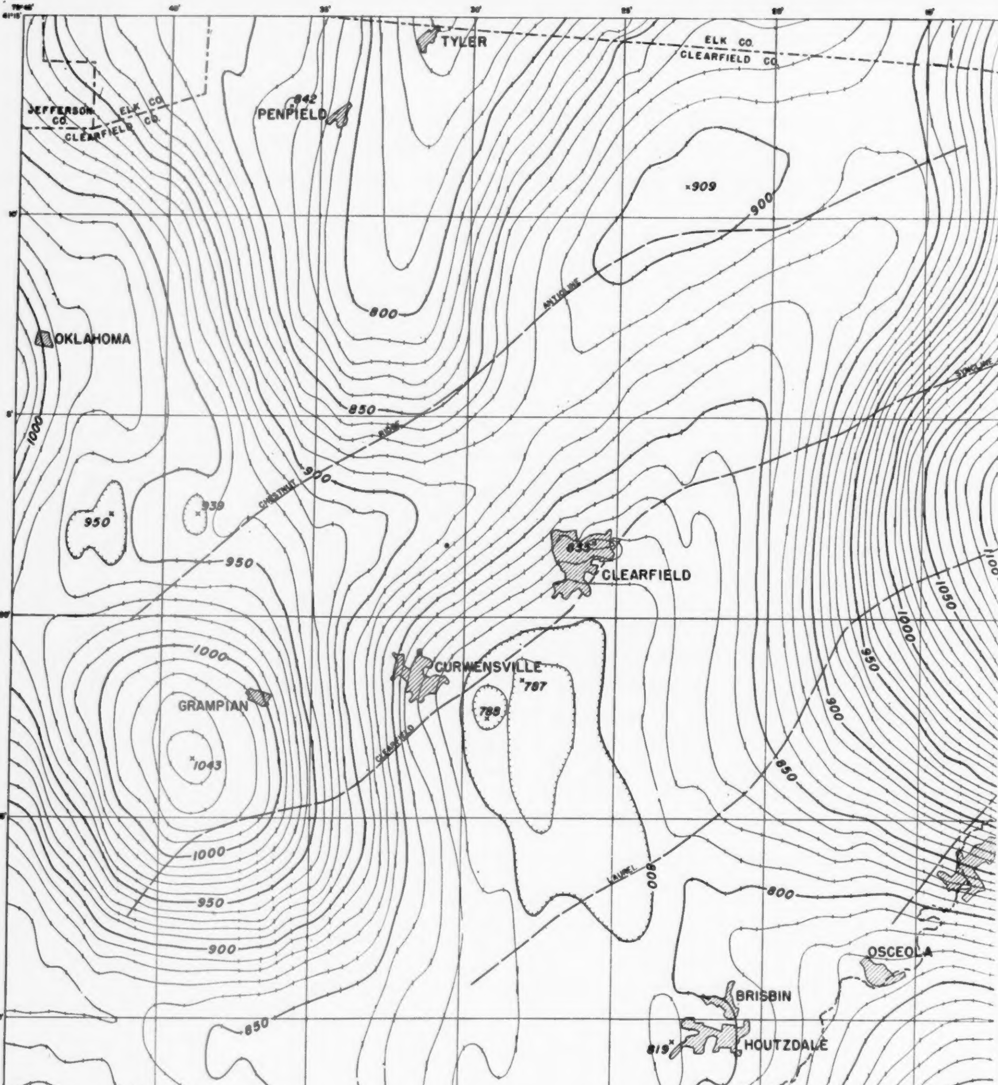
[2] United States Geological Survey. The project was conducted coöperatively by the United States Geological Survey and the Pennsylvania State College, School of Mineral Industries. The aeromagnetic survey was made by Fred Keller and Jack Meuschke of the Geological Survey, and the resulting data were compiled by L. O. Bacon and G. H. Crowl of the Pennsylvania State College. (S. J. Pirson and L. O. Bacon, "Airborne Magnetometer Survey of Central Pennsylvania," *Pennsylvania State Coll. Min. Indus. Exp. Sta. Bull. 48* (1947), pp. 55–65.) Final adjustments were made by George V. Keller, of the Pennsylvania State College, under the direction of Fred Keller. R. G. Henderson and I. Zietz of the Geological Survey made the theoretical computations. Considerable geologic information was supplied by Frank M. Swartz and Sylvain J. Pirson, chiefs of the divisions of geology and geophysics, respectively, of the Pennsylvania State College, and by S. H. Cathcart, State geologist of Pennsylvania. Their assistance is gratefully acknowledged.

[3] J. R. Balsley, "The Airborne Magnetometer," *U. S. Geol. Survey Geophys. Investig. Prelim. Rept. 3* (1946), p. 6.

A. W. Knoerr, "The Airborne Magnetometer—A New Aid to Geophysics," *Eng. and Min. Jour.*, Vol. 147, No. 6 (1946), pp. 70–75.

H. Jensen and J. R. Balsley, "Controlling Plane Position in Aerial Magnetic Surveying," *ibid.*, No. 8 (1946), pp. 94–95, 153–54.

Fred Keller, Jr., J. R. Balsley, Jr., and W. J. Dempsey, "Field Operations and Compilation



Base from U.S. Geological Survey Topographic Maps

AEROMAGNETIC MAP OF CLEARFIELD-PHILIPS

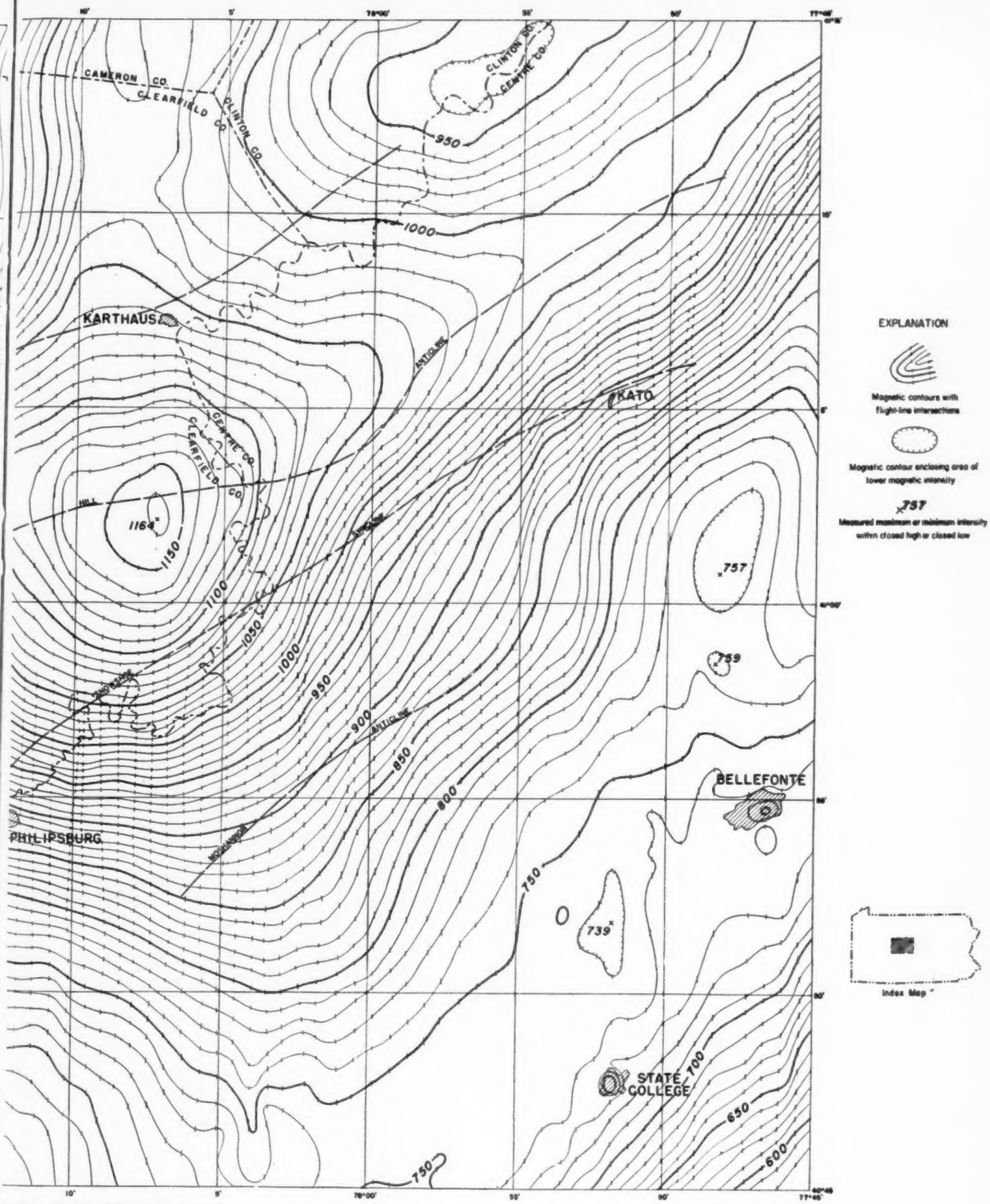
SHOWING VARIATION IN TOTAL IN

Contour interval 10 gammas

Flown approximately 1000 feet above surface

1948

FIG. 1



LIPS
AL IN
Miles

BURG AREA, PENNSYLVANIA
TENSITY
Miles

Aeromagnetic survey flown in 1946
by F Keller and J Meuschke
Compiled by L Bacon, F Keller
G Keller and others

FIG. 1

magnetic profiles thus obtained were tied to east-west magnetic base lines flown near the north and south boundaries and midway across the area. The three east-west base lines were joined by two north-south base lines, flown near the east and west boundaries of the area. All base lines were flown in two directions to permit elimination of instrumental drift and diurnal variation. The closing error of the 160-mile base-line net around the entire area totalled 5 gammas. This error was considered too small to distribute.

After the flight paths of the traverses were plotted on the 15-minute quadrangle topographic maps of the area, total intensity magnetic values were transferred from the profiles and contours were drawn at 10-gamma intervals. The contours as originally plotted showed noticeable "chevron" or "herringbone" effects in some areas. These deviations are a function of the direction of flight, which alternates from line to line. Detailed examination showed that in areas of low magnetic gradient chevron effects resulted from errors as small as 2 gammas. As the deviations are systematic rather than random, and as they are the result of slight inaccuracies in the base map on which the traverses were plotted, and in measurement and compilation of the data, the obvious chevrons were eliminated by smoothing. The maximum shift of any contour as a result of the smoothing was less than $\frac{1}{2}$ contour interval and the mean shift was 2 gammas.

GEOLOGIC SUMMARY

Most of the area is in the Allegheny Plateau, but the southeast corner extends into the adjoining Valley and Ridge Province (Fig. 2). The two physiographic provinces are separated by the Appalachian Front, a prominent scarp which is the approximate demarcation between the tight folds and large thrust faults of the Valley and Ridge Province on the southeast, and the broad open folds of comparatively low amplitude of the Allegheny Plateau on the northwest.

All the exposed sedimentary rocks are Paleozoic in age; they range from Upper Cambrian in the southeast part of the area to Middle Pennsylvanian in the northwest. The thickness of the exposed section is 21,000 feet, and the total thickness, including the underlying Middle and Lower Cambrian rocks, is estimated to be 25,000 feet.[4] The dominant structural feature in the southeast part of the area is the Nittany arch, which is essentially one great anticlinal fold on which are imposed numerous lesser folds and which is cut by thrust faults of considerable magnitude. The main arch as well as the minor folds are asymmetric, the northwest limbs dipping more steeply than the southeast. In addition, the fault planes dip generally southeast, indicating that they were produced by forces

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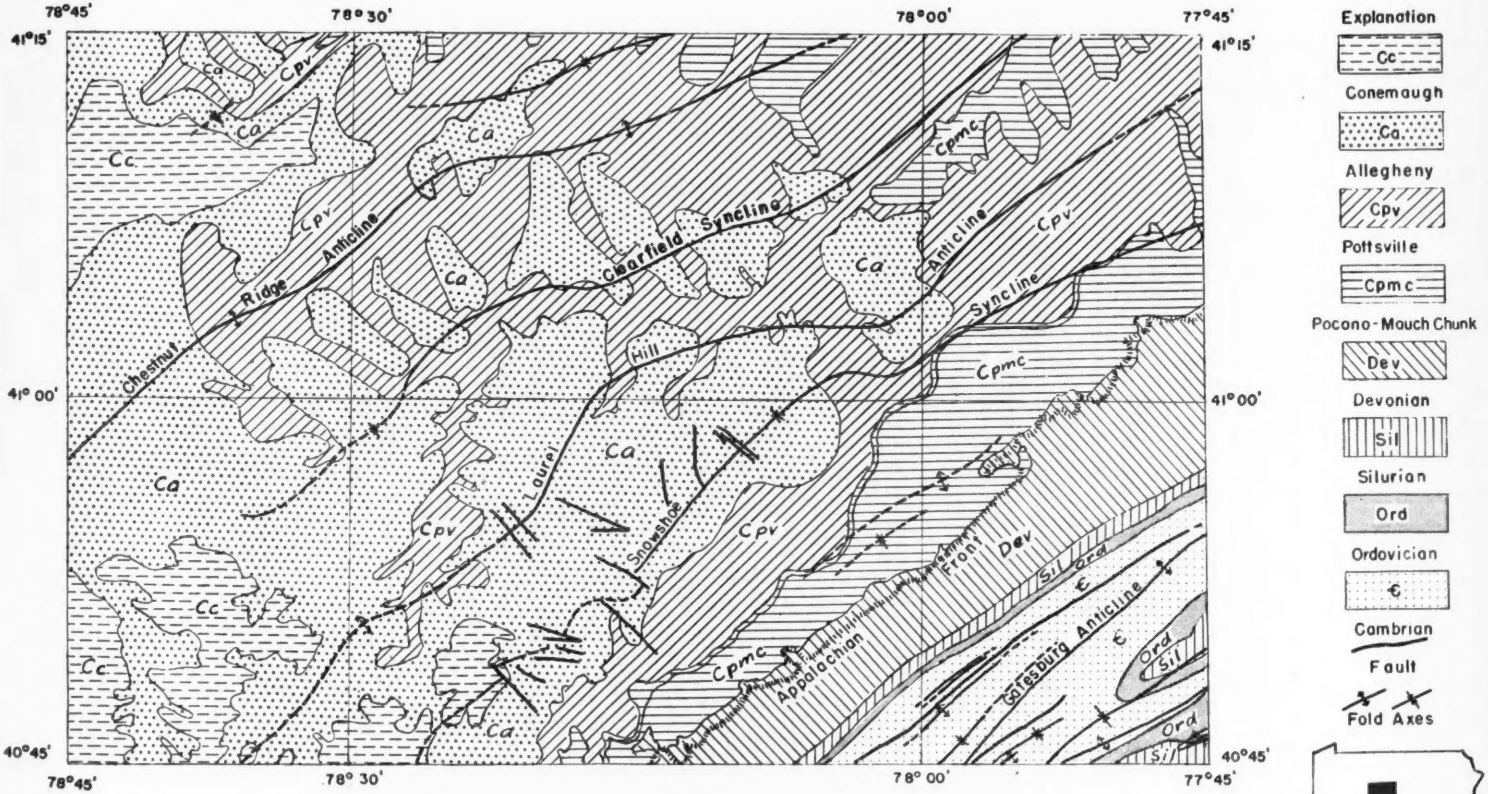
Procedure Incidental to the Preparation of Isomagnetic Maps," *Photogram. Eng.*, Vol. 13, No. 4 (1947), pp. 644–47.

[4] G. H. Ashley, "Geology of the Curwensville Quadrangle, Pennsylvania," *Pennsylvania Topog. and Geol. Survey*, Vol. 75 (1940), p. 43.



GENERALIZED GEOLOGIC MAP OF
CLEARFIELD—PHILIPSBURG AREA, PENNSYLVANIA

FIG. 2

acting from the southeast.[5] In the plateau area northwest of the Appalachian Front the surface structure is dominated by a series of shallow but persistent anticlines and synclines which trend northeast-southwest, and which diminish in amplitude and intensity on the northwest. Structurally, the area is part of a broad basin or synclinorium between the strongly folded mountains on the southeast and the Cincinnati arch on the west. According to geologic evidence, the main axis of the basin is just west of the Appalachian Front. The thickness of Paleozoic rocks along the axis is estimated to be 25,000 feet.[6]

No pre-Cambrian crystalline rocks or younger igneous intrusives are exposed in the Clearfield-Philipsburg area, nor are any known to have been found by drilling. The character of the basement rocks must therefore be inferred from that of the pre-Cambrian rocks in near-by regions.

Pre-Cambrian rocks are found in the Adirondacks on the northeast, in the Jersey Highlands and Piedmont on the east, and in the Blue Ridge Mountains on the southeast. In the Adirondacks they consist of metamorphosed sediments of the Grenville series and of intruded granites, syenites, and anorthosite, together with local concentrations of magnetic iron ore. In eastern Pennsylvania they likewise consist of gneisses of sedimentary origin, intruded by gabbros, anorthosite, and granites; whereas in the Blue Ridge Mountains of southern Pennsylvania the pre-Cambrian rocks consist of a thick series of metabasalts and metarhyolites.

In view of the heterogeneous character of the pre-Cambrian rocks in near-by regions, it is inferred that the basement rocks in central Pennsylvania are comparably heterogeneous. Furthermore, the northeast-striking structures of the pre-Cambrian rocks in those regions are essentially parallel with the elongated Appalachian troughs of Paleozoic sediments and with the subsequent Appalachian folding.[7] It is probable, therefore, that the trends of the basement rocks in central Pennsylvania are in general similar to those of the overlying sediments.

It is similarly inferred by Swartz[8] on the basis of geologic evidence in near-by regions that the basement rocks were deformed during Appalachian folding concordantly with the larger folds in the Paleozoic sediments; that is, the basement rocks are generally arched under anticlines and depressed under synclines. Evidence based on drilling in the Allegheny Plateau further indicates that some of the Appalachian folds were active during Paleozoic sedimentation, and that the

[5] Charles Butts and E. S. Moore, "Geology and Mineral Resources of the Bellefonte Quadrangle, Pennsylvania," *U. S. Geol. Survey Bull. 855* (1936), p. 80.

[6] Frank M. Swartz, "Geologic Aspects of Petroleum Exploration in Pennsylvania," *Pennsylvania State Coll. Min. Indus. Exp. Sta. Bull. 48* (1947), pp. 66–80, Fig. 1.

[7] Frank M. Swartz, "Trenton and Sub-Trenton of Outcrop Areas in New York, Pennsylvania, and Maryland," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 8 (1948), p. 1513.

[8] *Ibid.*, p. 1584.

amplitudes of these folds increase in the lower Paleozoic rocks and presumably in the basement.[9]

No younger igneous rocks are known to occur in the Clearfield-Philipsburg area; however, peridotite dikes have been found in western Pennsylvania and in adjoining parts of New York and West Virginia.[10] It follows that similar small peridotitic dikes may have intruded the sediments in the area under consideration.

TOTAL INTENSITY AEROMAGNETIC MAP

Major features on the aeromagnetic map (Fig. 1) are: (1) two prominent highs, southwest of Curwensville and south of Karthaus, respectively, (2) a marked southeast gradient in the southeast part of the area, and (3) a general northeast alignment of the main magnetic trends. Minor features are: (1) a small reversal in the Bellefonte-State College area, and (2) numerous minor irregularities of obviously shallow origin.

Possible causes of the major magnetic features are: (1) large-scale magnetic heterogeneity of the pre-Cambrian basement rocks, (2) large basic intrusions in the sedimentary rocks, (3) concentrations of magnetic material or magnetic strata in the Paleozoic rocks, and (4) great topographic relief of the underlying pre-Cambrian surface.

Magnetic heterogeneity of the basement rocks is believed to be the dominant cause of the larger magnetic anomalies, on the basis of both geological and theoretical considerations. Geologic evidence indicates that the basement rocks underlying the Allegheny Plateau are comparable in composition and structural trend with those in the Adirondack and Piedmont regions. In addition, the magnetic anomalies are comparable in magnitudes and trends, when allowance is made for the thickness of the sedimentary section.

To estimate depths to the basement, a method originated by Vacquier and further developed by Henderson, Zietz, and Steenland was employed.[11] It is assumed that the anomalies arise from inhomogeneities in the basement rocks and that the basement can be divided into vertical prismatic cells within which the rock is homogeneous and polarized by induction in the earth's magnetic field. A second vertical derivative map of the observed field is then compared with that computed for suitable prismatic models, to determine likely maximum depths to the tops of the bodies that produce the magnetic anomalies. The method is of course valid only when the underlying assumptions are met and when the theoretical and observed anomalies are comparable.

[9] R. E. Sherrill, "Possible Future Oil Pools of Pennsylvania," *National Oil Scouts and Landmen's Association Year Book* (1945), p. 557.
Frank M. Swartz, *op. cit.*, p. 1584.

[10] A. P. Honess and C. K. Graeber, "Petrography of the Mica Peridotite Dike at Dixonville, Pennsylvania," *Amer. Jour. Sci.*, 5th Ser., Vol. 12 (1926), pp. 484–94.

[11] A discussion of this method will be published in a memoir of the Geological Society of America.

Applied to the Curwensville magnetic high, the method places the top of the magnetic body approximately 19,000 feet beneath the surface. A similar application to the Karthaus high yields a depth of 19,000–22,000 feet. As these depths agree with the estimated thickness of the overlying Paleozoic rocks, the initial assumption regarding inhomogeneity appears to be satisfied. However, there is no assurance that the tops of these magnetic bodies coincide with the surface of the basement rocks. They may also be basic differentiates within the pre-Cambrian basement, the tops of which lie beneath the surface of the basement; or they may be younger basic intrusives in the lower Paleozoic rocks and thus rise above the surface of the basement. No unique answer can be obtained from the magnetic data.

The lack of close agreement between the magnetic and surface structural features indicates that the major anomalies are not caused by magnetic zones in the Paleozoic rocks. Furthermore, there appears to be no geologic evidence of large concentrations of magnetic material in the Paleozoic rocks, such as would be required to produce the Curwensville and Karthaus magnetic highs.

Topographic relief of the pre-Cambrian surface is also discarded as a major factor, as an improbably great relief would be required to produce the large magnetic anomalies observed over the Allegheny Plateau. To produce the Curwensville high, for example, a basement relief of 15,000 feet would be required, with an assumed intermediate susceptibility contrast of 0.004 centimeter-gram-second unit and a basement datum 30,000 feet beneath the surface; and 10,000 feet of relief would be required if the basement is 20,000 feet beneath the surface (Fig. 3). Considerably greater basement relief would be required to produce the Karthaus magnetic high because of its greater amplitude.

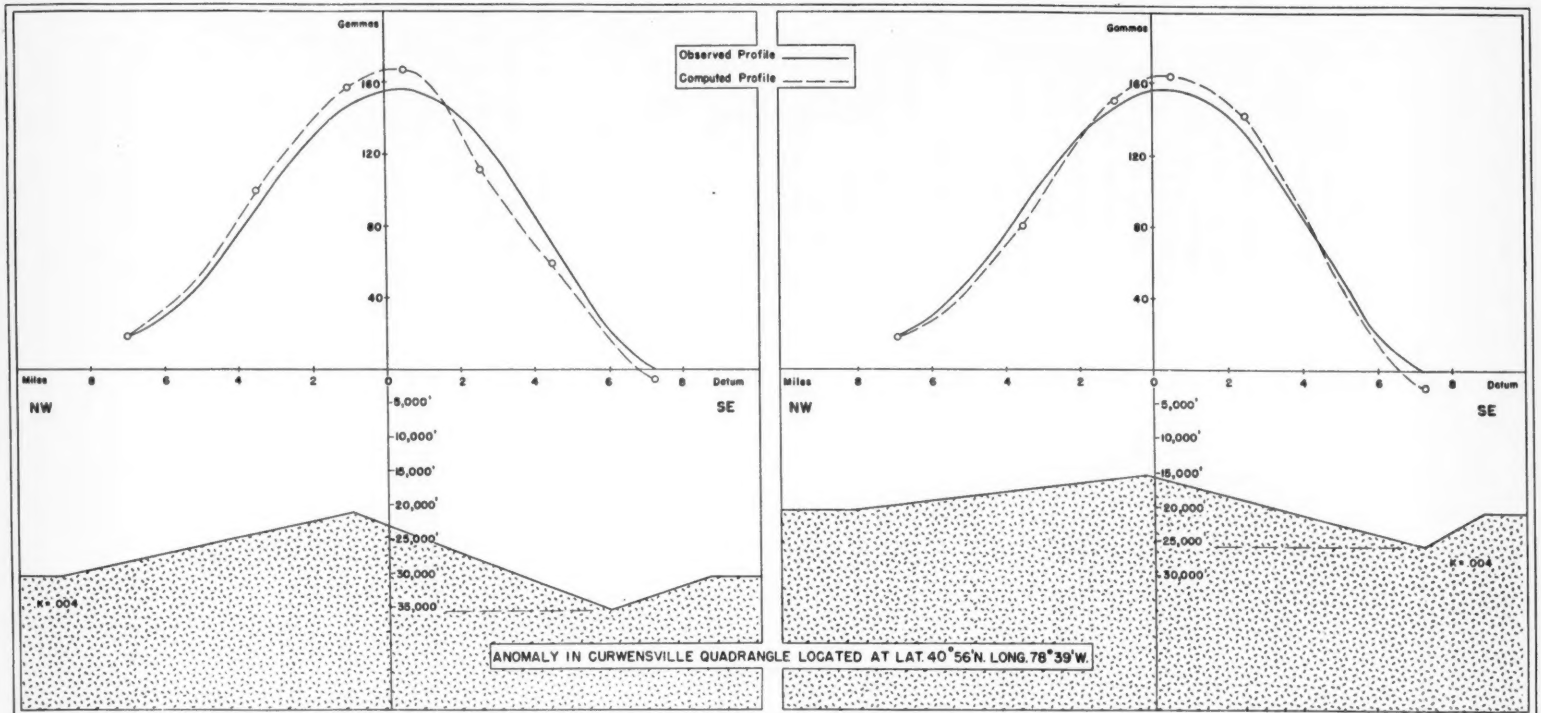
The assumption of basement relief as the major cause of the Curwensville and Karthaus highs becomes still more untenable when it is considered that they are associated with folds of comparatively low amplitude; the Nittany arch, which is the largest structural feature in the area, is apparently reflected by only a minor reversal in the magnetic gradient.

It is nevertheless apparent from surface evidence in eastern Pennsylvania, at least, that the surficial parts of the pre-Cambrian rocks were involved in Appalachian folding and associated displacements. The Mine Ridge anticline is a classic example of structural concordance of the pre-Cambrian with the overlying Paleozoic rocks. According to Swartz[12] there is some evidence that various Appalachian folds were incipiently active during Paleozoic sedimentation; and according to Sherrill[13] the amplitudes of some of the anticlines of the Allegheny Plateau increase with depth, so that the effects of basement topography can not be entirely ignored.

A folded basement of uniform, positive susceptibility would of course give

[12] Frank M. Swartz, *op. cit.*, p. 1584.

[13] R. E. Sherrill, "Possible Future Oil Pools of Pennsylvania," *National Oil Scouts and Landmen's Association Year Book* (1945), p. 557.



BASEMENT RELIEF REQUIRED TO APPROXIMATE OBSERVED MAGNETIC ANOMALY

FIG. 3

rise to magnetic anomalies generally coincident with the fold axes. Unfortunately, the basement is not magnetically uniform; and in the plateau region where the folds are small, these anomalies would be obscured by anomalies resulting from susceptibility differences within the basement.

Without complete information on the magnetic susceptibilities of the rocks involved, no method of separating topographic anomalies from those caused by susceptibility variations is known. It would nevertheless be of interest to determine the magnetic expression of a pre-Cambrian surface of uniform susceptibility, deformed somewhat concordantly with the overlying sedimentary rocks. Figure 4 shows the computed and observed magnetic profiles over such a hypothetical pre-Cambrian section in the Clearfield-Philipsburg area. In constructing this section, the basement relief under the low-amplitude anticlines of the plateau area was assumed to be several times that of the corresponding folds at the surface, whereas the basement was assumed to rise 15,000 feet under the Nittany arch in concordance with surface structure.

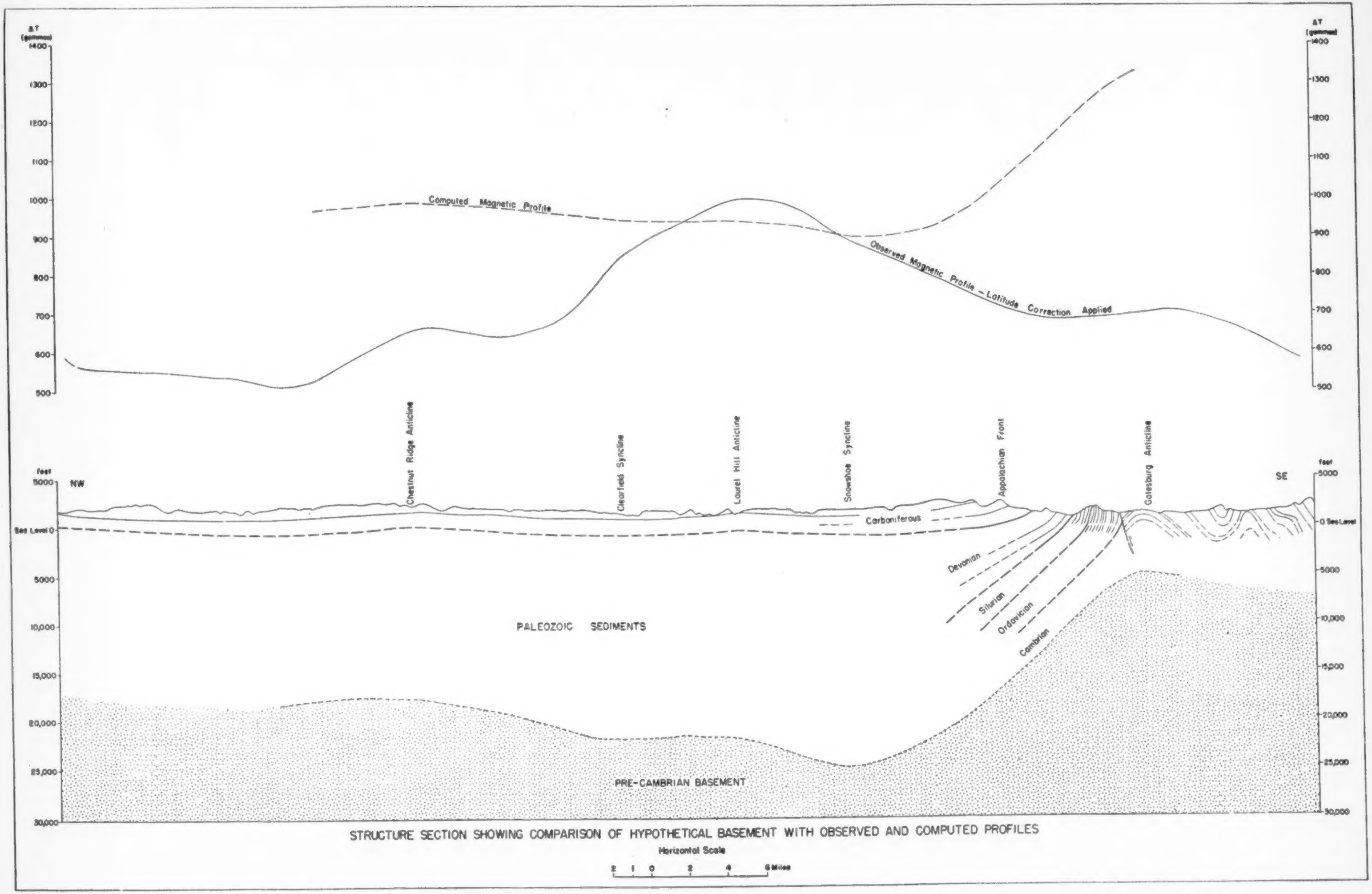
Comparison of the magnetic profiles observed over the plateau with those computed for a uniform susceptibility contrast of 0.004 c.g.s. unit shows that the magnetic expression of a more or less conformable pre-Cambrian surface is so small that it would normally be masked by anomalies resulting from susceptibility differences. However, the observed profile over the Nittany arch shows a much smaller amplitude than the computed profile; and the observed magnetic intensity decreases southeastward, whereas it would normally be expected to increase.

Possible causes of these discrepancies are: (1) as already suggested by Pirson and Bacon,[14] the pre-Cambrian surface is not even approximately concordant with surface structures along the Nittany arch, and in fact dips southeast, and (2) the observed gradient is the result of a gradational southeastward decrease in magnetism within the pre-Cambrian rocks. A combination of these two causes is also possible.

If the large-scale or resultant susceptibility of the pre-Cambrian rocks is uniform and on the order of 0.004 c.g.s. unit, then the negative southeastward magnetic gradient indicates a corresponding increase in depth of nearly 3,500 feet in 10 miles. As it is improbable that the large-scale susceptibility of the pre-Cambrian rocks is entirely uniform, it is also improbable that it decreases uniformly over a considerable distance, or that it varies so that little effect on the magnetic field is produced by a fold with an amplitude of 15,000 feet.

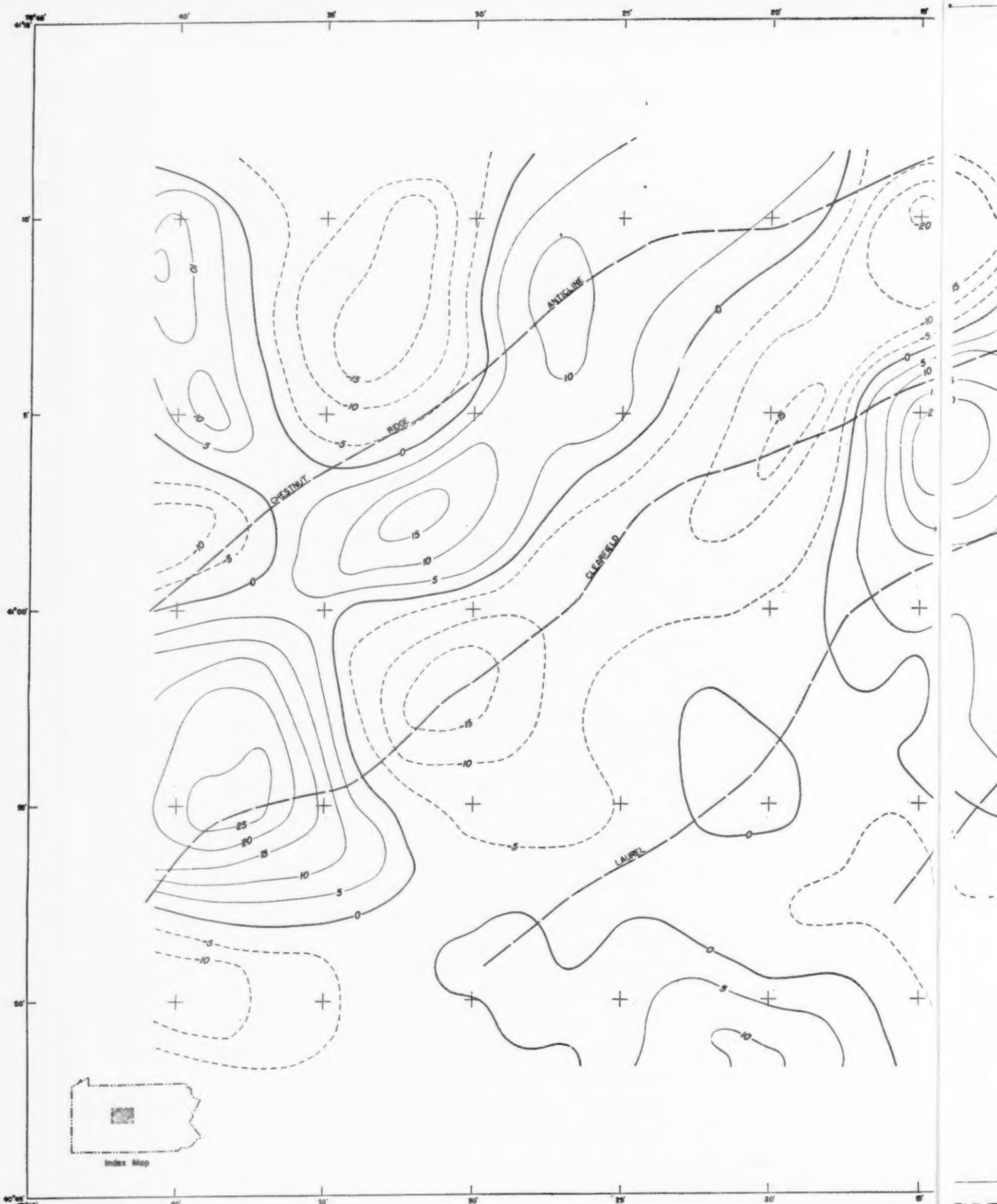
A unique answer concerning the configuration of the pre-Cambrian surface is not possible because the susceptibilities of the basement rocks are not known. In addition, only a small part of the Valley and Ridge Province was covered by the aeromagnetic survey. The available magnetic evidence nevertheless indicates that although the basement may rise under the Nittany arch, it is not concordant with surface structure in the vicinity of State College and Bellefonte.

[14] S. J. Pirson and L. O. Bacon, *op. cit.*, p. 61.



STRUCTURE SECTION SHOWING COMPARISON OF HYPOTHETICAL BASEMENT WITH OBSERVED AND COMPUTED PROFILES

FIG 4



Base from U.S. Geological Survey
Topographic Maps

AEROMAGNETIC MAP OF CLEARFIELD- PHILIP

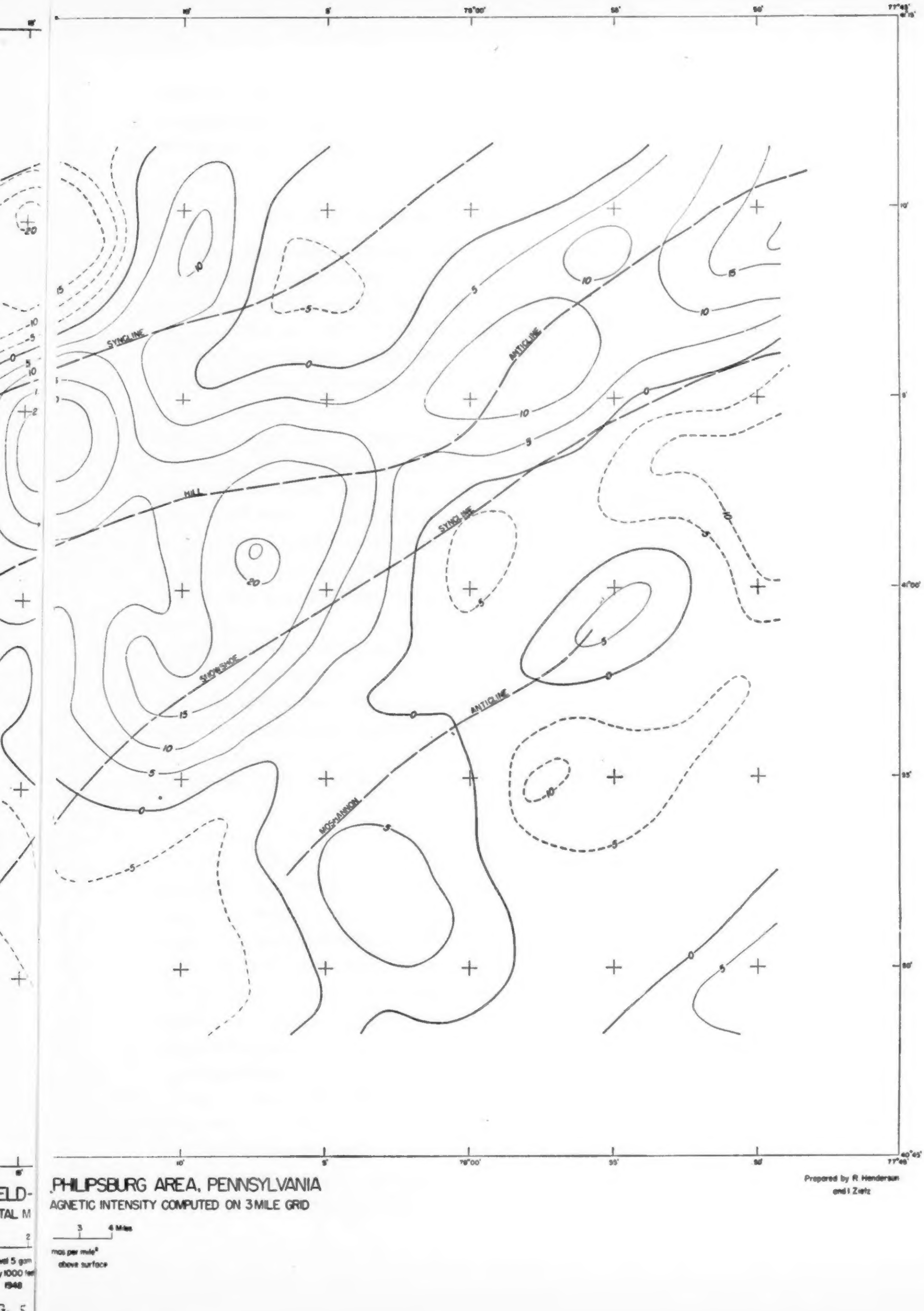
SHOWING SECOND VERTICAL DERIVATIVES OF TOTAL M AGNETIC

Contour interval 5 gam

Flown approximately 1000 fee above surf

1948

FIG. 5



ELD-
TAL M

PHILIPSBURG AREA, PENNSYLVANIA
AGNETIC INTENSITY COMPUTED ON 3 MILE GRID

3 4 Miles

mos per mile²
above surface

Prepared by R. Henderson
and I. Zietz

G. 5

In fact, the indicated depth of the crystalline basement is considerably greater than that inferred from the estimated thickness of the buried Paleozoic sediments. A correlative inference is that the maximum depth to the basement is southeast of the Appalachian Front, rather than northwest.

SECOND-DERIVATIVE ANALYSIS OF DEEP-SEATED MAGNETIC TRENDS

As already stated, the trends observed on the aeromagnetic map (Fig. 1) coincide approximately with the folding at the surface, but they are obscured by major discordant features such as the Curwensville and Karthaus highs. Accordingly, a magnetic map was prepared showing variations in the second vertical derivative of magnetic intensity ($\partial^2 T/\partial z^2$). A 3-mile grid, sufficiently large to minimize the effects of anomalies of small areal extent, was used in computing the second vertical derivatives.

The resulting map (Fig. 5) emphasizes the predominant northeast alignment of the major magnetic trends, but it also shows that they strike N. 45° E., whereas the fold axes strike N. 60° E. The major magnetic trends apparently reflect structural trends of a magnetically heterogeneous basement, which has been strongly folded and eroded, and probably intruded by basic igneous rocks. The divergence between the basement and surface trends indicates a corresponding divergence of direction of the forces which produced the structures in the pre-Cambrian and Paleozoic rocks.

An insufficient area was covered to determine whether the indicated divergence is local or regional. It is probable, however, that greater or lesser discrepancies exist between structural trends in the pre-Cambrian and Paleozoic rocks throughout the Appalachians, as a result of local or regional variations in tectonic forces. In any event, the indicated divergence may have complicated the apparently simple folds of the Allegheny Plateau, and may be an important consideration in exploring the deeper anticlines in that region.

SECOND-DERIVATIVE ANALYSIS OF SHALLOW MAGNETIC FEATURES

Although the major magnetic features observed in the Clearfield-Philipsburg area apparently originate in the deeply buried pre-Cambrian basement, minor features are obviously of near-surface origin. In order to emphasize these minor features, most of which appear only as slight irregularities on the total intensity map, a second-derivative map based on a one-mile grid was constructed (Fig. 6).

This map emphasizes sharp, local changes in the magnetic gradient. It follows that errors in observation, compilation, or drafting, which produce sufficiently sharp changes in gradient, will be emphasized, as well as valid anomalous features. Due caution should therefore be observed in the interpretation of the indicated anomalies.

Many of the more prominent second-derivative anomalies shown in Figure 6 apparently indicate the presence of near-surface magnetic differentiates. Those near Houtzdale are associated with minor faults striking normal to the main

fold axes; others do not coincide with any known structural or other geologic anomalies. Two very conspicuous highs over the towns of State College and Bellefonte are obviously related to artificial magnetic fields. Many of the smaller anomalies are of dubious validity, since they coincide with chevrons on the total-intensity map which could not be smoothed by any reasonable or objective process.

Detailed ground magnetic surveys and geologic examinations would be required to test the validity of the various shallow anomalies indicated on the second-derivative map, and to determine their causes.

MAGNETIC MAP OF PENNSYLVANIA

The area covered by the aeromagnetic survey is large by most standards, but it is small in comparison with the observed magnetic features and with the regional geologic features of the Allegheny Plateau and the Valley and Ridge Province. A total-intensity magnetic map of the entire state of Pennsylvania was therefore constructed (Fig. 7), to permit comparison of magnetic features and their relation to surface structure in a larger area with those in the Clearfield-Philipsburg area. Values of the total magnetic intensity for 98 stations scattered throughout the state were computed from horizontal-intensity and inclination data published by the Coast and Geodetic Survey.[15] Aeromagnetic data were used in the Clearfield-Philipsburg area, which is outlined by dashed lines in Figure 7. Because of the wide spacing of stations, the map indicates magnetic trends only in a general way. In addition, some of the larger anomalies may be delineated incorrectly, because they are based on single-station observations.

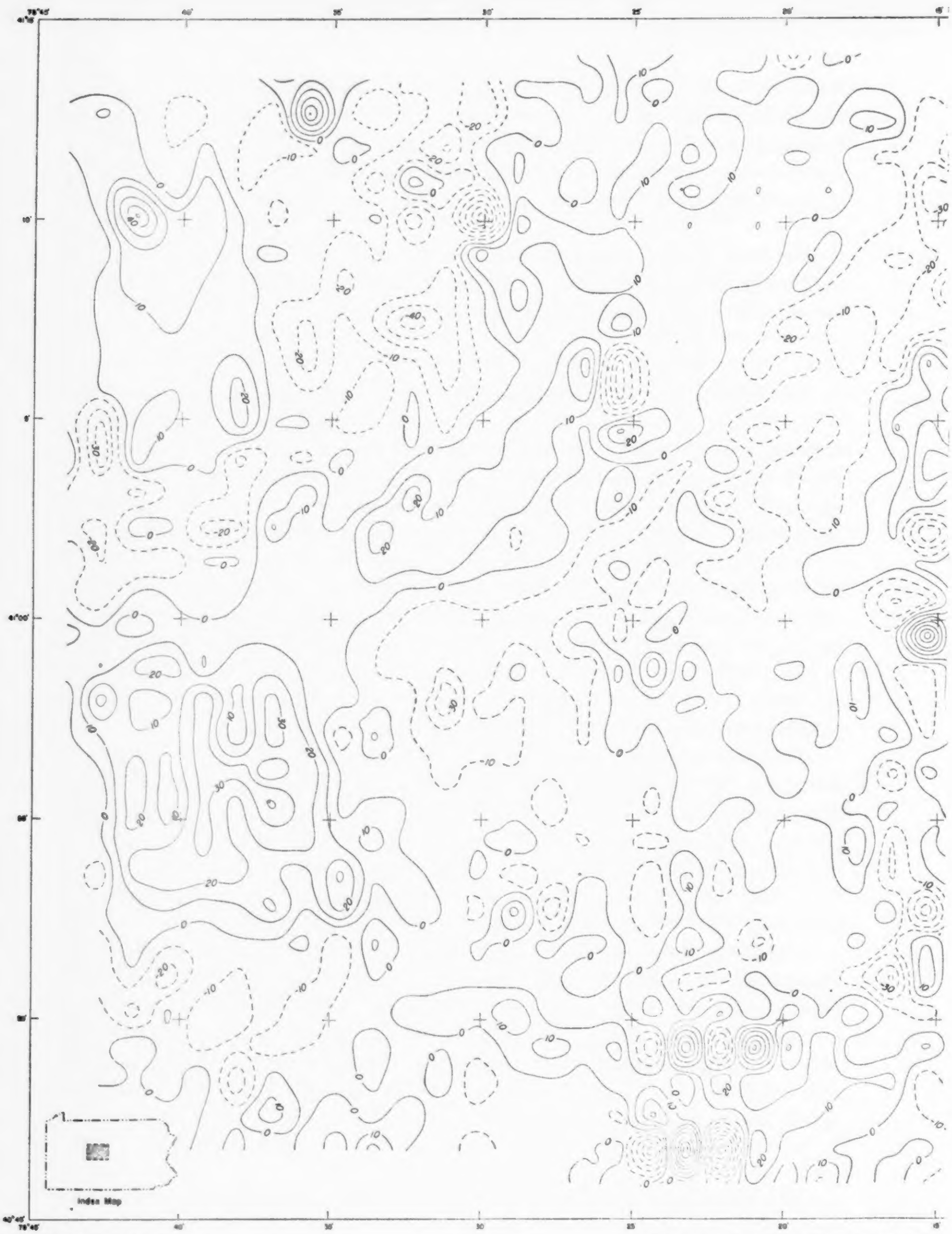
The indicated magnetic trend in the Appalachian region is N. 60° E. It is therefore only approximately in accord with Appalachian folding, as the fold axes strike N. 30° E. in the southern part of the state and then curve along a great arc until they strike N. 60°–70° E. in the central and eastern parts. These divergences indicate corresponding divergences of structural trends in the pre-Cambrian and Paleozoic rocks. It must be emphasized, though, that more complete magnetic data may alter the magnetic trends shown in Figure 7.

The negative southeastward magnetic gradient observed along the Nittany arch in the Clearfield-Philipsburg area (Fig. 1) is shown to continue many miles farther southeast. Although no unique solution of the significance of this negative gradient is possible, it implies that the pre-Cambrian and Paleozoic rocks may not be folded concordantly in parts of the Valley and Ridge Province, and that the axis of the structural basin may be southeast of the Appalachian Front, rather than northwest.

SUMMARY AND CONCLUSIONS

The major magnetic features in the Clearfield-Philipsburg area are related

[15] "United States Magnetic Tables and Magnetic Charts for 1935," *U. S. Coast and Geodetic Survey Serial 602* (1938).



Base from U.S. Geological Survey
Topographic Maps

AEROMAGNETIC MAP OF CLEARFIELD
SHOWING SECOND VERTICAL DERIVATIVES OF TOTAL M

Contour interval 10 ga
Flown approximately 1000
1946

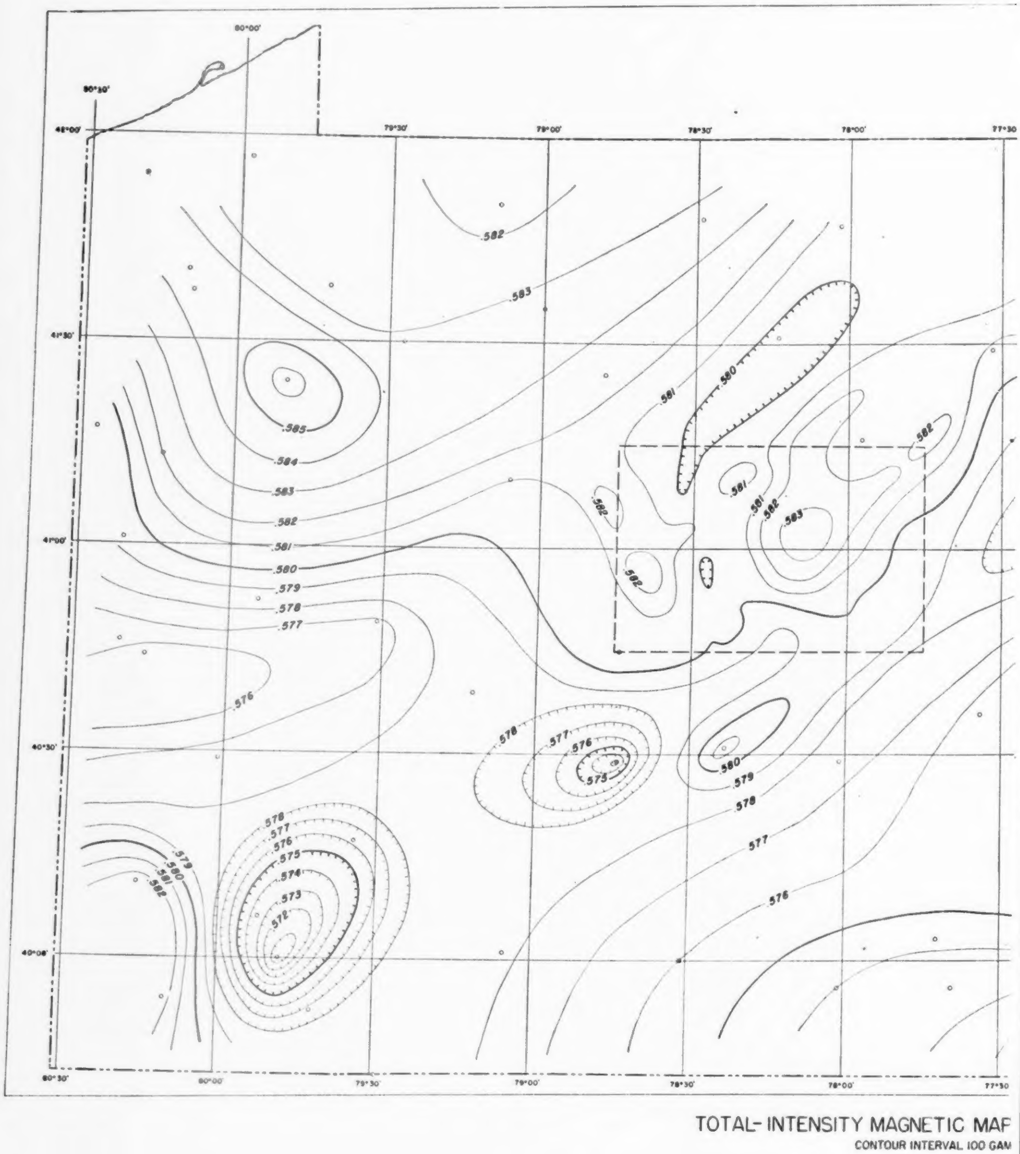
FIG. 6

-PHILIPSBURG AREA, PENNSYLVANIA
AGNETIC INTENSITY COMPUTED ON ONE-MILE GRID

Prepared by R. Henderson
and I. Zietz

2 3 4 Miles

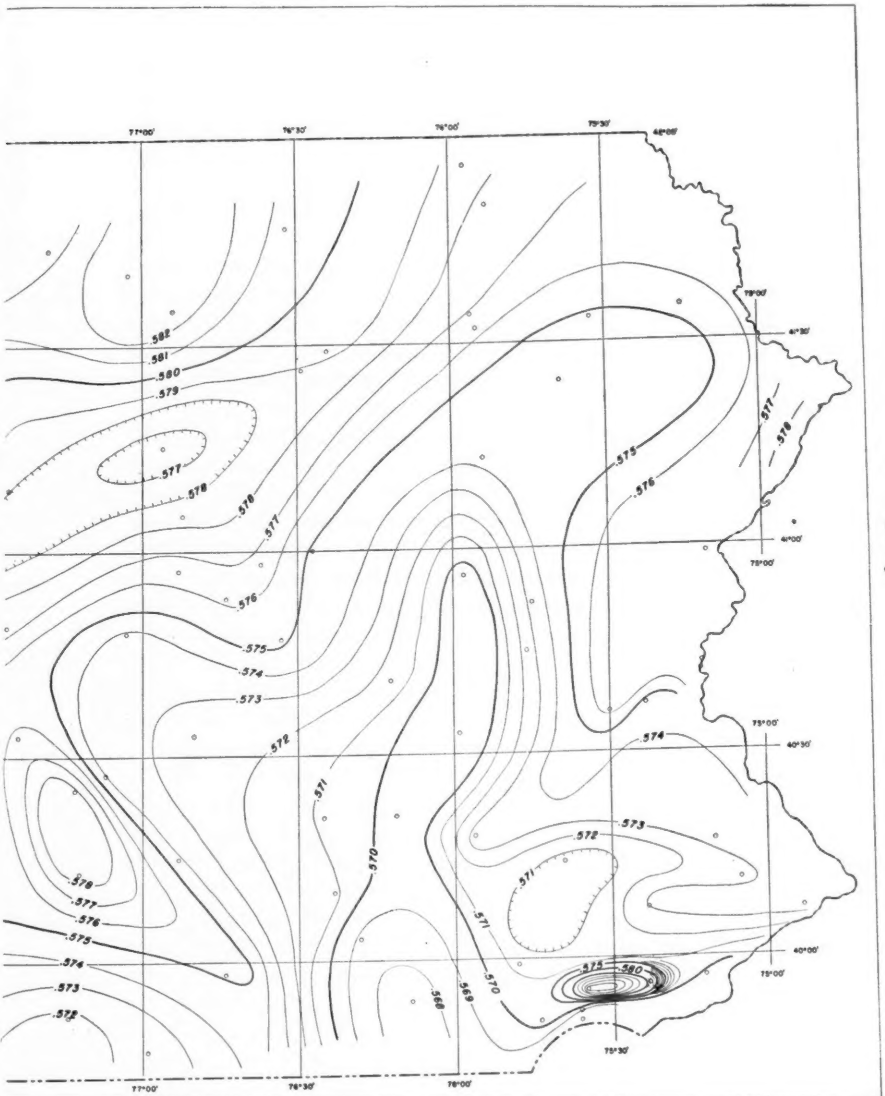
mmas per mile²
feet above surface



TOTAL- INTENSITY MAGNETIC MAF

CONTOUR INTERVAL 100 GAM

FIG. 7



EXPLANATION

Boundary of area covered by aeromagnetic survey

Coast and Geodetic Survey magnetic station

OF PENNSYLVANIA

MAS

predominantly to large-scale variations in the magnetic susceptibility of the pre-Cambrian basement. With the possible exception of a minor magnetic high over the Nittany arch, indicating a partial concordance of the basement with the overlying Paleozoic rocks, there is no discernible coincidence of magnetic configuration with the known structures of the area. In fact, according to the magnetic evidence, depth to the basement is greatest southeast of the Appalachian Front rather than northwest. Magnetic anomalies related to basement relief in the Allegheny Plateau are probably small and therefore masked by those relating to susceptibility variation in the basement.

The principal magnetic trends, which strike N. 45° E., apparently reflect trends in the geologically complex basement. It follows that the divergence of these trends from the surface structural trends, which strike N. 60° E., indicates a corresponding divergence of pre-Cambrian and Paleozoic lineation.

Minor anomalies are of shallow origin, and indicate small comparatively shallow concentrations of magnetic material.

The trends on a state-wide magnetic map agree with Appalachian structural trends only in a general way. The lack of close agreement may indicate divergence of regional lineation of the pre-Cambrian and Paleozoic rocks, or it may be due to the sparse data on which the map is based. The state-wide map is therefore of value mainly in pointing out the potentialities of regional aeromagnetic surveys of the Appalachians, to furnish regional information on the pre-Cambrian rocks and on their relation to the overlying sedimentary rocks.

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VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1767-1769

GEOLOGICAL NOTES

APPROACH TO ORIGIN OF OIL[1]

WALTER K. LINK[2]
New York, N. Y.

In the search to the answer of "oil origin" many ideas and theories have been advanced. Most geologists agree that oil originates from organic materials in sediments, preferably marine.

The oil industry with scientific societies, research groups, and universities, has given considerable thought and money to the problem, but the answer or answers are still far away. It is hoped that the conclusions derived from these studies will aid the geologist and industry in finding more and cheaper oil.

Geologists have looked for the answer by studying oil fields and the sediments adjacent to and associated with these deposits. The method of approach has been the study of the ancient sediments in oil-producing regions. This certainly is, or was, a logical approach, even if one subscribes to comparatively long-distance migration of oil. The oil must have been derived from the sediments within the basin or basins of oil-producing areas.

The formation of petroleum from organic substances is a chemical process, but it is not clear how these processes worked. From the sediments within an oil area, the geologist can fairly accurately determine the source of sediments, the environment of deposition, rate of deposition, temperature, and a host of other factors, all of which must have played an important part in the process of oil formation. In spite of all these leads no clear-cut answer has been obtained.

In the past, and even now, geologists talk rather freely about oil-forming formations or mother rock. These are very vague terms and certainly are nothing specific to go on. In areas where oil is reservoired in sand, and the overlying and underlying beds are shales, they assume that the oil was derived from these sources, especially if there are indications of organic and fossil content. They talk about color, texture, and a host of other theoretical leads, but in most of the adjacent rocks there is little or no trace of oil origin. Even if they were the source, what happened to the by-products, or aren't there any? Perhaps the chemical processes are such complete ones that everything turns into oil, leaving little or nothing for the chemist to work on. It is also noteworthy that possible reservoirs in conjunction with oil shales or black shales do not invariably carry oil, even on good structure. Could it be that these highly carbonaceous shales, from which something that looks like oil is obtained, are fossil mother rock, or have still-born oil which never got out for some reason or other?

Research work sponsored by the American Petroleum Institute, the American

[1] Manuscript received, August 15, 1949.

[2] Chief geologist, Standard Oil Company (New Jersey).

Association of Petroleum Geologists and other organizations, has followed the line of reasoning that the processes of oil formation could be as follows.

1. The accumulation of organic materials in sediments
2. The transformation of this organic material into hydrocarbons
3. The change of these hydrocarbons into real petroleum—called maturing of oil

Of these three points we are mainly concerned with the processes of transformation of organic material into petroleum. Some of the suggested processes are:

a. Bacterial action
b. Radioactivity
c. The purely chemical activity along with temperature, pressure and time, and in the presence of, and with the aid of, catalysts

Under certain conditions it is conceivable that petroleum can be formed by any one of the three alone, but it is more logical to believe that all three acted on the same materials to form petroleum.

So far, not much progress has been made by working on the ancient sediments. This may be due to the fact that the scientists do not know how to handle what is left after petroleum has been formed, especially from the chemical side, and also that different and not the same materials have been used in the experiments. The writer therefore suggests the reverse approach, namely, that the use of young sediments instead of ancient ones be tried.

Geologists have a fairly good idea under what conditions oil was formed. They also know there are places in the world to-day where oil should be forming if their ideas are reasonably correct.

The processes of oil formation must begin as soon as sediments are deposited and, if nothing happens, should continue to completion. In the Gulf of Mexico along the Louisiana and Texas Gulf Coast the conditions of deposition, temperature, *et cetera*, seem to be almost the same now as they were in Tertiary time. There is much Tertiary oil in that region, and furthermore, there is some accumulation in Pliocene sediments. Whether it originated in the Pliocene sediments or not is subject to question.

At any rate, there is a considerable sedimentary column consisting of Recent, Quaternary, and Pliocene down to the Tertiary, where geologists are certain oil was formed. Furthermore, sedimentation has been almost continuous, as this region has had no important movements other than tilting, normal faulting, and salt-dome growth.

If the processes of oil formation, or the alteration of organic materials into hydrocarbons, take place upon deposition and continue, then oil should be forming in the Gulf Coast and other basin areas to-day. No one knows what comes first—gas, heavy hydrocarbons, light hydrocarbons, waxes, or what.

The writer believes that the processes of oil formation in the earth are mainly chemical, and that the answer to oil origin must be approached from that angle. This means that organic chemical analysis techniques will have to be experimented with and perfected to do the job.

A systematic foot-by-foot analysis of sediments, starting with the youngest

and going down to the oldest, in which oil is known to exist, should be carried out. If oil, or the material from which oil is formed, begins to form early in the stage of deposition and burial, then careful analysis of sediments should indicate what the early and subsequent alterations of organic material into petroleum are, and eventually a hydrocarbon or a recognizable oil may be detected on a very small scale, disseminated through the sediments.

The collection of samples and material, for analysis, will be an important, and probably an expensive, part of this project. The following methods might be employed.

1. Collection of bottom samples in a present-day depositional basin (Gulf of Mexico). The A.P.I. project on Sedimentology, if carried out, would be an excellent way to get such samples.
2. Wells are being drilled in the waters and swamps of the Gulf Coast. One or more of these wells should be cored continuously and in as sterile a manner as possible.
3. All methods of analysis, that is, chemical, bacterial and radioactive, should be used on the same samples, foot by foot.
4. If at all possible, wells that have a good chance of becoming producers from the older sediments below, should be chosen for coring.

If oil is forming to-day in young sediments, then chemical analysis should reveal the presence of the first clues to hydrocarbon formation and the resulting changes of continued chemical activity and geologic processes. It must be remembered that sedimentary load and pressure alteration will be at work with depth. The process of transformation to rock will also be accurately gauged, and the results of load on different types of sedimentary materials, such as muds, sands, silts, and shell limestone beds.

The results of temperature will also be evaluated. Geologists have always placed much stress on temperature. It may be found or proved that normal sea-bottom temperatures of warm waters are sufficient to start the processes of oil formation, and that oils are generated and completed in a relatively low-temperature environment. Tertiary oils certainly suggest this possibility.

The idea that oil took a long time to form may be a fallacy. Much oil is found in old formations, but this does not mean that the oil found in these formations took a long time to form originally. Time may have altered this oil to the extent that older oils appear to have somewhat different characteristics and a lighter gravity. The older rocks in general had many more oil pools associated with them than are present in those formations to-day. During geologic time and the processes of earth movement many oil pools were destroyed, and we are looking only at those that were fortunate enough to survive, or at traps that caught the redistributed oil. In oil areas the Tertiaries and Cretaceous generally show the most surface manifestations of oil and gas. The reason for this may not be because the Tertiary rocks generated more oil, but because there has been less time for this oil to have become dissipated. Because of this belief, the writer thinks that the key to oil origin lies in the sediments now being deposited, and in the examination of the young sediments in basin areas (such as the Gulf Coast) where sedimentary and environmental conditions appear to be much the same as in Tertiary time, an era of great oil formation.

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VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1770-1776

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and are available, for loan, to members and associates.

FORAMINIFERA OF THE AQUITAINE BASIN, BY J. CUVILLIER AND V. SZAKALL

REVIEW BY HANS E. THALMANN[1]
Caracas, Venezuela

"Foraminifères d'Aquitaine," by J. Cuvillier and V. Szakall. Première Partie (Reophacidae à Nonionidae). 112 pp., 32 pls. Published (1949) by the Société Nationale des Pétroles d'Aquitaine, 26, rue de la Pépinière, Paris 8 (F. Boisseau, Toulouse).

The literature of fossil Foraminifera is rich in monographs dealing with single formations, or with the systematic treatment of one or a few outcrops of the same formation. The micropaleontologists welcome, therefore, the appearance of this regional monograph, which catalogs and figures all Foraminifera found in the formations present in the Aquitaine basin of southwestern France.

More than 10,000 outcrop samples have been systematically searched for Foraminifera since 1942 in the laboratories at Dax and Toulouse of the Société Nationale des Pétroles d'Aquitaine. The two authors were assisted in this tremendous task by Miss M. Texier, Miss Hartopp, J. P. Nicolas, J. Kikoine, Mrs. Y. Gubler, J. Dupouy-Camet, A.Debourle, and R. Chabosi.

The present volume comprises the families Reophacidae, Ammodiscidae, Lituolidae, Textulariidae, Verneuilinidae, Valvulinidae, Miliolidae, Ophthalmidiidae, Trochamminidae, Orbitolinidae, Lagenidae, Polymorphinidae, and Nonionidae (following Cushman's classification). A second and final volume, including everything from Nummulitidae to Miogypsinidae, is scheduled to appear in print in 1950.

The 13 families treated are represented by 81 genera of Foraminifera, of which one is a new genus, *Daxia* (family Lituolidae). The numbers of species cited and figured total 495, of which 14 are new; in addition, there are 7 varieties listed and 77 forms to which the nomenclatura aperta was applied. Comments are given regarding the individual forms, with the exception of the fully described new genera and species. No synonymies are listed, but the original citation for each species is given. All forms, ranging from Lower Cretaceous to Recent, are well reproduced on 32 photographic plates, which give an excellent picture of the foraminiferal content in the Aquitaine basin.

There is one important point in the nomenclatural treatment of the genera and species described, which the reviewer would bring to the attention of the authors: Article 23 of the International Rules of Zoological Nomenclature has not been followed throughout the work and, therefore, should be strictly adhered to in the forthcoming second part. In not following this important rule, some homonyms have been erected, as f.i. *Dentalina cornicula* (d'Orbigny), (originally published as a *Nodosaria*, 1826) vs. *Dentalina cornicula* Seguenza, 1880, or *Marginulina incerta* (Egger, *Cristellaria*, 1857) vs. *Marginulina incerta* Neugeboren, 1851. A few misprints may be quoted: Cushman's latest (fourth) edition of his well known text-book was edited in 1948 (not 1947); *Valvulina* d'Orbigny was erected in 1826 (not 1862); *Marssonella* Cushman in 1933 (not 1926); *Listerella* Cushman, 1933 has to be replaced by *Schenckiella* Thalmann, 1942; the figures cited for *Coskinolina liburnica* Stache do not refer to this species; *Nummoloculina* Streimann should read Steinmann;

[1] Venezuelan Atlantic Refining Company. Review received, August 22, 1949.

Spiroloculina tenuissima (Reuss) is regarded as a *Sigmoilina; Biloculinella ventruosa* Reuss should be *ventricosa;* the genotype of *Orbitolina* d'Orbigny is not *O. gigantea* d'Orb. (which is possibly a coral), but *O. concava* Lamarck, 1801; *Flabellina* d'Orbigny, 1839 should be replaced by *Palmula* Lea, 1833; *Frondicularia* Defrance was erected in 1824 (not 1826); Cusmhan in the bibliographic list should read Cushman, and Glaesser Glaessner.

In spite of these minor mistakes, the two authors and their co-workers should be highly commended for the publication of this regional monograph. The reviewer fully shares their wish that other oil companies release the amount of invaluable informations stored in their private files, and urge their micropaleontologists to edit regional monographs so that our field of knowledge of fossil foraminiferal assemblages might be enlarged and every one interested in foraminiferology could profit by such publications.

Micropaleontologists all the world over will certainly look for the publication of the second (and concluding) part of this monograph, and also for the plates of thin sections of hard rocks announced by the authors in the Foreword. Such an Atlas would make it possible to study more intimately characteristic microfacies of sediments, which are as important as cataloged regional monographs.

POLYCHAETE ANNELIDS FROM THE DEVONIAN OF PARANÁ, BRAZIL, BY FREDERICO WALDEMAR LANGE

REVIEW BY KENNETH E. CASTER[1]
Cincinnati, Ohio

*"Polychaete Annelids from the Devonian of Paraná, Brazil," by Frederico Waldemar Lange (Museu Paranaense, Curitiba, Paraná, Brazil). *Bulletins of American Paleontology*, Vol. 33, No. 134 (June, 1949). 102 pp., 16 collotype pls., 3 text figs.

The Paleontological Research Institution (126 Kelvin Place, Ithaca, New York) is to be congratulated for this excellent publication which is a revised and amplified English translation of the author's 1947 paper in Portuguese published in the Archives of the Museu Paranaense in Curitiba.

Lange's paper has considerable importance in amplifying our knowledge of the Austral Devonian fauna and stratigraphy; but of far greater significance is its timely demonstration of paleontologic method and caution in the handling of difficult and fragmental micromaterials. It would have been most unfortunate had the paper been permanently hidden to most workers outside the Latin American world, as it would have been had it not been republished.

As the reviewer indicated in previous reviews[2] of the Portuguese edition, Lange's paper is possibly the most significant paper yet published on scolecodonts (fossil worm jaws); certainly so in recent years. This is the first record of polychaete jaws in the Austral Devonian, and for that matter, in South America; possibly for the Southern Hemisphere. Although scolecodonts have been known for nearly a century, and at many Paleozoic and Mesozoic horizons, especially in North America and Europe, never before has a single completely articulated jaw assemblage been described. The ordinary occurrence is as discrete jaw elements, which have customarily been assigned generic and specific names, in accordance with common paleontologic practice. Lange has two complete jaw-sets and several incomplete ones; these are complemented by many hundred disjunct jaw

[1] Department of geology and geography, University of Cincinnati. Review received, September 8, 1949.

[2] *Jour. Paleon.*, Vol. 22, No. 5 (September, 1948), pp. 647–48. *Amer. Jour. Sci.*, Vol. 246, No. 11 (November, 1948), pp. 724–25.

elements. The collection represents several years of patient work in field and laboratory.

Under ordinary circumstances, and usual paleontologic procedure, such a rich collection would have afforded several new "genera" and many new "species." Lange, however, shows admirable patience and great caution; he painstakingly studied each component of the complete buccal armature, and made detailed dissections of modern polychaetes from the Brazilian littoral. He was then able to show that the sizeable array of "genera" and "species" in his collection, on the basis of the usual scolecodont study technique, is entirely assignable to a single new genus and species. Moreover, it becomes definitively certain that only complete buccal assemblages offer a valid basis for taxonomy of the group.

Lange's painstaking paleontologic and neontologic comparisons illuminate the inadequacies of current scolecodont studies. Economic, or other teleological expediency can hardly justify bad paleontologic procedure. On the basis of Lange's paper a strong case could be (and perhaps should be) made to the proper International Authority for the suppression of considerable paleontologic "taxonomy" based on invalid criteria. Paleontologists must cease to misuse Systematics (a biologic art); and should they continue to do so (usually in the interest of economic paleontology and/or stratigraphy), they must expect to encounter sanctions, if not downright hostility, from the biologic profession. Our treatment of many groups of problematical remains, including the most useful, but enigmatic conodonts, tracks, trails, and spoor or remains of comparable ilk as meriting taxonomic treatment in accordance with the rules of biologic nomenclature can not help bringing the whole science of paleontology into disrepute in the eyes of discerning neontologists. Sooner or later an enormous amount of such paleontologic "taxonomy" must be discarded, but this is no easy matter, and "the sins of the fathers . . . " must necessarily clutter systematic literature, apparently so long as systematic sciences exist.

Lange's excellent paper forces these cardinal issues to the forefront; it could serve as a splendid text for a long, soul-searching sermon addressed to a considerable number of paleontologic practitioners, among whom the reviewer should no doubt listen attentively.

PETROLEUM EXPLORATION IN EASTERN ARKANSAS WITH SELECTED WELL LOGS, BY CHARLES A. RENFROE

REVIEW BY T. H. PHILPOTT[1]
Shreveport, Louisiana

"Petroleum Exploration in Eastern Arkansas with Selected Well Logs," by Charles A. Renfroe. *Arkansas Division of Geology Bull. 14* (Little Rock, 1949). 159 pp., 3 pls., 2 figs.

This bulletin summarizes the subsurface geologic data that have been obtained from representative logs of each county in eastern Arkansas. In part the report augments "List of Arkansas Oil and Gas Wells"[2] by listing the wildcat wells that have been drilled since 1937.

Most of the data were selected from the log file of the Division of Geology at Little Rock, Arkansas, and deal specifically with fifty-eight key well logs. The log information consists of a driller's log supplemented where possible by lithologic, paleontologic, and electric-log data.

Little editing was done in many of the drillers' logs included since they are subject to rather broad interpretations. The author has deleted all notations "shows of oil or gas," due to the fact that most of these so-called "shows" are not authentic.

[1] The Carter Oil Company. Review received, September 15, 1949.

[2] *Arkansas Geol. Survey Information Circ. 10* (1937).

All of the plates included are of interest to any geologist desiring to familiarize himself with the geology of the area. Plate I is a base map of eastern Arkansas showing the location of all wildcat wells deep enough to be considered tests. The company name, the lease name, the total depth, and the surface elevation are plotted for each wildcat.

In recent months the Division of Geology of the Arkansas Resources and Development Commission has initiated an active program to preserve and re-interpret data on previously drilled wells. Plates II and III are the combined electric, lithologic, and drilling-time logs of two key wells, furnishing a starting point for future correlations. Figure 2 is a general columnar section of the Cenozoic and part of the Cretaceous section as encountered in most of the wells in this area.

At the beginning of each county unit there is a list of wells which includes all known locations of wells of appreciable depth drilled before January 1, 1949. The list designates those wells with available drillers' logs and wells in which an electric survey was made. These wells are tabulated by owner, lease, section-township-range, total depth, elevation, and date drilling was started and completed.

In many ways eastern Arkansas is as little explored geologically as any major province in the entire country. Although many wells have been drilled in eastern Arkansas in the past several years, less than two dozen are of any value for the purpose of oil exploration. At present, development in eastern Arkansas is in the exploratory state. It is at the point now, as far as the scientific recording of subsurface data, where the Mid-Continent area and the state of Texas were 20 years ago. No oil pools have been discovered and comparatively large areas still remain untested. In a matter of time, the question of the presence of oil pools should be answered because the complex stratigraphy is gradually being worked out. Only a very few wells have been drilled on geologic or seismic data, most of the wells being drilled as the result of hit-or-miss wildcatting.

The author believes that the chances for accumulations of oil in rocks of Tertiary age are exceedingly remote and that the best possibilities for Cretaceous oil are the Nacatoch and basal Upper Cretaceous sandstone.

The Nacatoch is an excellent potential reservoir bed if found on a structure with enough closure, or associated with those conditions that will provide a stratigraphic trapping of the oil.

At present very little is known about the stratigraphy or the oil and gas possibilities of the Paleozoic rocks. Porous zones are known to be present in several of the Ordovician formations. Asphaltic showings are fairly common in the Paleozoic, having been found in Missouri in rocks as old as Cambrian.

The reviewer finds that this bulletin brings up to date the oil exploration developments in eastern Arkansas. The well prepared text, illustrations, and selected well logs provide the basic data for any geologist studying this area.

RECENT PUBLICATIONS

ARCTIC REGION

* "Topography and Sediments of the Arctic Basin," by K. O. Emery. *Jour. Geol.*, Vol. 57, No. 5 (Chicago, September, 1949), pp. 512–21, folded map.

BRAZIL

*"Breves notícias sôbre a geologia dos estados do Paraná e Santa Catarina" (Brief Survey of Geology of the States of Paraná and Santa Catarina), by Reinhard Maack. *Paraná Inst. Biol. e Pesquisas Tecnol. Arquivos de Biologia e Tecnológia*, Vol. II, Art. 7 (Curitiba, 1947), pp. 63–154; 135 figs. (photographs and text figs.), 4 folded geologic maps

and stratigraphic sections (1948). Paper covers. 6.25×9 inches. Originally written as text to accompany the "Geological Map of South America." Portuguese. Abstracts in English and German, 2 pp. each. Instituto de Biologia e Pesquisas Tecnológicas, Secretaria de Agricultura, Industria e Comércio, Curitiba, Paraná. Price, Cr $50.

*"Lycopodiopsis Derbyi Renault, documento da idade Paleozóica das camadas Terezina do Brasil meridional" (*Lycopodiopsis Derbyi* Renault, Evidence of Paleozoic Age of Terezina Beds of Southern Brazil), by Reinhard Maack. *Ibid.*, Vol. II, Art. 8, pp. 155–208; 34 figs. A new stratigraphic table and sections explain the reorganization of the Gondwana beds. Price, Cr $30.

COLOMBIA

*"Geologia de la Costa sur del Pacifico de Colombia" (Geology of the Pacific Coast of Colombia), by Victor Oppenheim. *Inst. Geofisico de los Andes Colombianos*, Ser. C, Bol. 1 (Bogota, July–August, 1949). 23 pp., 6 figs., 3 photographs. Spanish. Abstract (1 page) in English.

GENERAL

Digest (1949). Tulsa Geological Society annual publication of abstracts and summaries of papers delivered at its meetings during the year from October, 1948, to May, 1949. Edited by John C. Maher. 196 pp., 32 illus., 23 digests. Contains directory of Tulsa Society members and company affiliations. Copies available from V. L. Frost, Ohio Oil Company, Thompson Building, Tulsa, Oklahoma. Price, $1.00.

The Meaning of Evolution, by George Gaylord Simpson. 364 pp., 38 figs., Cloth. Outside dimension, 5.5×8.25 inches. A study of the history of life and of its significance for man. Yale University Press, New Haven, Connecticut (1949). Price, $3.75.

GERMANY

**Erläuterungen zur Geotektonischen Karte von Nordwestdeutschland* (Explanation for Geotectonic Map of Northwest Germany), prepared by the Reichsamt für Bodenforschung Hannover-Celle (Geologisches Landesamt). Edited by A. Bentz. Foreword (English) by E. A. Gunther. Collaborators: H. Aldinger, H. Closs, Fr. Dahlgrün, K. Hoffmann, H. Lögters, E. Malzahn, H. Reich, W. Schott, O. Seitz, and R. Wager. 235 pp. Paper cover. 5.5×8 inches. In German. 24 map sheets have been published. Scale: 1 to 100,000. Each sheet approx. 31×27 inches, outside dimensions. In colors. "It is the aim of this map to include all geological, geophysical, and drilling data relevant to the exploration for and the winning of crude oil." Prepared by order of British Oil Fields Investigation 912 Military Government. Distributed (1949) by the Amt für Bodenforschung, Guterbahnhofstrasse 5–15, Celle (20a), Germany, British Zone. Price (maps and book), 300 marks (approx. $100).

KANSAS

*"Oil and Gas in Eastern Kansas," by John Mark Jewett. *Kansas Geol. Survey Bull. 77* (Lawrence, July, 1949). 308 pp., 53 figs., 4 pls., 81 tables. 6×9 inches. Paper cover.

MEXICO

**Geología de México*, by Valentin R. Garfias and Theodore C. Chapin. 202 pp. More than 600 bibliographic titles. 4 figs., including a geologic map of Mexico on a sheet 27×17 inches. Paper cover. 7×9.5 inches. In Spanish. Editorial Jus, Mexico (1949).

NEW MEXICO

*"New Mexico Oil and Gas Engineering Data for 1948," compiled by E. E. Kinney, Lea County Operators Committee, and New Mexico Conservation Commission. *New Mexico Bur. Mines and Min. Resources Oil and Gas Rept. 4-B* (Socorro, 1949). 353 pp. Multigraphed. 8.5 ×11 inches. Paper cover. Price, $2.25.

*"Carlsbad Caverns and Other Caves of the Guadalupe Block, New Mexico," by J Harlen Bretz. *Jour. Geol.*, Vol. 57, No. 5 (Chicago, September, 1949), pp. 447–64; 5 figs.

*"Geomorphic History of the Carlsbad Caverns Area, New Mexico," by Leland Horberg. *Ibid.*, pp. 464–76; 3 figs., 1 pl.

*"The Ogallala Formation West of the Llano Estacado," by J Harlen Bretz and Leland Horberg. *Ibid.*, pp. 477–90; 2 figs., 2 tables, 1 pl.

*"Caliche in Southeastern New Mexico," by J Harlen Bretz and Leland Horberg. *Ibid.*, pp. 491–511; 8 figs., 2 tables.

NETHERLANDS

*"Eindverslag van het Geophysische Omderzoek in Zo.-Nederland" (Geophysical and Geological Survey of Southeastern Netherlands), edited by L. U. de Sitter. *Mededeelingen van de Geol. Stichting*, Ser. C-I-3-No. 1 (1949). 372 pp. (1–261 in Dutch; 262–365 in English), 73 figs., 2 pls. Paper covers. Approx. 7.75 ×10.50 inches. 24 folded maps, charts, sections boxed, separate from text, approx. 8×11×2 inches. Uitgevers-Mij. "Ernest van Aelst," Maastricht. Price, fl. 30.

PORTUGAL

*"Planifiçacão Histórico-Cronológica das Pesquisas de Petróleo em Portugal" (Historical-Chronological Account of Search for Petroleum in Portugal), by Fernando A. C. Gonçalves Maciera. *Serviço de Fomento Mineiro Estudos, Notas e Trabalhos*, Vol. 4, Fasc. 2 (Porto, Portugal, 1949), pp. 68–164; 20 pls., 2 folded maps. Portuguese.

ROCKY MOUNTAINS

"Paleocene Deposits of the Rocky Mountains and Plains," by Roland W. Brown. *U. S. Geol. Survey Map* (August 1949). Scale, 1:1,000,000. Includes column and text. May be purchased from Director, U. S. Geological Survey, Washington 25, D. C. Price, $0.60.

TENNESSEE

"Pre-Chattanooga Stratigraphy in Central Tennessee," by Charles W. Wilson, Jr. *Tennessee Div. Geology Bull. 56* (1949). 407 pp., 89 figs., 28 pls. Paper cover. 6×9 inches. Foreword by State geologist H. B. Burwell. Tennessee Division of Geology, G-5 State Office Building, Nashville, Tennessee. Price, $2.65.

TEXAS

*"Origin of Shallow Structures in West-Central Texas," by G. H. Brodie. *World Oil*, Vol. 129, No. 6 (Houston, Texas, September, 1949), pp. 61–66; 2 figs.

UTAH

*"Rock Alteration as Guide to Ore—East Tintic District, Utah," by T. S. Lovering in collaboration with W. M. Stoll, A. H. Wadsworth, H. V. Wagner, B. F. Stringham, H. T. Morris, Lowell Hilpert, J. F. Smith, Alberto Terrones L., F. G. Bonorino, J. W. Odell, and E. Mapes V., *Monograph 1, Economic Geology*, Economic Geology Publishing Company, Urbana, Illinois (1949). 64 pp., 12 figs., 5 pls.

WYOMING

"Electric-Log Correlation Chart of the Wind River Basin and Adjacent Areas of Wyoming," by Correlation Committee of the Wyoming Geological Society. Two sheets, 40×72 inches and 24×40 inches. Commonly accepted correlation of strata from lower Upper Cretaceous to pre-Cambrian. Available from Petroleum Information, Box 2452, Casper, Wyoming. Price for set of two: $3.00, folded; $3.25, rolled in tube.

ASSOCIATION DIVISION OF PALEONTOLOGY AND MINERALOGY

**Journal of Sedimentary Petrology* (Tulsa, Oklahoma), Vol. 19, No. 2 (August, 1949).

"Sorting of Sediments in the Light of Fluid Mechanics," by Douglas L. Inman.

"Synthesis of Sand Mixtures," by Henry W. Menard, Jr.

"Missouri River Sediments in River Water, Ocean Water and Sodium Oxalate Solution," by W. D. Keller and Richard Foley.

"Ripple Marks as an Aid in Determining Depositional Environment and Rock Sequence," by O. F. Evans.

"The Origin of the Verden Sandstone of Oklahoma," by O. F. Evans.

**Journal of Paleontology* (Tulsa, Oklahoma), Vol. 23, No. 5 (September, 1949).

"Nomenclatural Units and Tropical American Miocene Species of the Gastropod Family Cancellariidae," by Jay Glenn Marks.

"Review of the Lower Cretaceous Fresh-Water Molluscan Faunas of North America," by Teng-Chien Yen.

"A New Rudistid from the Niobrara of Colorado," by Mary O. Griffitts.

"Foraminifera from the Asagai Formation (Tertiary) of Fukushima Prefecture, Japan," by Kiyoshi Asano.

"The Foraminiferal Genus *Cruciloculina d'Orbigny*, 1839," by Kiyoshi Asano.

"Rotaliid Foraminifera of the Chapmanininae: Their Natural Distinction and Parallelism to the *Dictyoconus* Lineage," by Don L. Frizzell.

"*Ferayina* in the Middle Eocene of Venezuela (Foraminifera, Rotaliidae, Chapmanininae)," by Maria de Cizancourt and Don L. Frizzell.

"Bibliography and Index to Foraminifera (Supplements and Corrections for the Period 1931 to 1947)," by Hans E. Thalmann.

"Three New Devonian Species of *Microcyclus* from Michigan and Ontario," by Erwin C. Stumm.

"Facial Sutures in the (Hypoparian) Trilobites *Loganopeltoides* and *Loganopeltis*, and the Validity of these Genera," by Frank Raw.

"Triassic Chimaeroid Egg Capsules from the Connecticut Valley," by Wilhelm Bock.

"The Relationships of the Alberta Cretaceous Dinosaur '*Laosaurus*' *minimus* Gilmore," by Loris S. Russell.

"*Alzadasaurus pembertoni*, a New Elasmosaur from the Upper Cretaceous of South Dakota," by S. P. Welles and James D. Bump.

"The Subspecies of *Hoplophoneus:* a Statistical Study," by Jean Hough.

"Small Mammals from the Uppermost Eocene (Duchesnian) near Badwater, Wyoming," by Albert E. Wood.

"Stereophotography as a Tool of the Paleontologist," by William R. Evitt, II.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1777-1783

THE ASSOCIATION ROUND TABLE

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* Terms of individuals expire at close of annual meeting in April of year indicated, unless another month is shown.

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PACIFIC SECTION FALL MEETING, NOVEMBER 17–18

The 26th joint annual meeting of the Pacific Section of the Association will be held at the Ambassador Hotel, Los Angeles, California, November 17 and 18. LOYDE H. METZNER, Signal Oil and Gas Company, is program chairman. The A.A.P.G. luncheon is scheduled for Thursday noon, November 17. The formal dinner dance is on November 18. Room reservations should be made by writing directly to the Ambassador.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

At the recommendation of the A.A.P.G. committee on national responsibility, in order to attain its objective "to plan and advise with the Military Services for the effective application of geology and the efficient functioning of geologists within the Military Services," the executive committee is requesting each applicant for membership to return a statement of his World War II service and his present reserve status, if any, for which purpose a special blank is furnished by Association Headquarters, Box 979, Tulsa 1, Oklahoma.

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 979, Tulsa 1, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

To comply with the new amendments affecting qualifications for membership, new applicants and their sponsors should hereafter use new (1949) application forms and the new (1949) constitution and by-laws. Old forms should be destroyed.

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Gerald Frank Bowers, Ann Arbor, Mich.
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Harold Dixon Fox, Natchez, Miss.
H. N. Hickey, F. E. Turner, Cyril C. Denny

Royal Austin Hartenberger, Seminole, Tex.
John P. Hughes, Robert M. Dreyer, William Henry Courtier
Ralph D. Hawkins, Los Angeles, Calif.
Loyde H. Metzner, Albert L. Ladner, Raymond Sidwell
Woodrow Wilson Hawthorne, Dallas, Tex.
B. M. Choate, O. C. Clifford, Jr., A. E. McKay
Hal Hicks Holland, Jr., Kingsville, Tex.
C. E. Buck, W. E. Dougherty, J. S. Dismukes
Thomas Barron Howes, New Orleans, La.
Hampton Smith, Gordon Bell, James H. Todd
James Irving Johnson, Denver, Colo.
Bernard M. Bench, Thad G. McLaughlin, S. W. Lohman
Kenneth C. Lamb, Ardmore, Okla.
Hobart E. Stocking, V. Brown Monnett, Ray L. Six
Paul Todd Landes, Jr., Lewisville, Ark.
V. E. Monnett, Carl A. Moore, John L. Edwards
Frank Allen Morrison, Corpus Christi, Tex.
James F. Gibbs, Carl A. Moore, Keith M. Hussey
Robert Allen Nesbit, Maracaibo, Venezuela, S. A.
A. I. Levorsen, T. W. Koch, H. M. Horton
Edwin Scott Parker, Taft, Calif.
John C. Wells, Antonie Paap, S. J. Kriz
Arthur Moxon Patterson, Calgary, Alta., Canada
F. G. Fox, J. R. Shouldice, F. A. McKinnon
William Lynn Peyton, Oklahoma City, Okla.
Carl A. Moore, Glenn C. Clark, Everett C. Parker
James Watson Proctor, Jackson, Miss.
E. T. Monsour, Frederic F. Mellen, David C. Harrell
John Samuel Reeder, Jr., Houston, Tex.
Olin G. Bell, H. J. McLellan, R. L. Denham
James Varnell Sexton, Magnolia, Ark.
H. V. Howe, Richard Joel Russell, Grover E. Murray
Virgil Elmer Spradlin, Tulsa, Okla.
F. A. Melton, Carl A. Moore, V. E. Monnett
Donald Frederick Todd, Ionia, Mich.
A. J. Eardley, George V. Cohee, K. K. Landes
William James Vaughn, Jr., Amarillo, Tex.
Edwin M. Rowser, Harold E. Schwartz, K. K. Landes
Fred Somervill Watson, Jr., Okmulgee, Okla.
E. L. Lucas, Carl A. Moore, Wesley G. Gish

FOR TRANSFER TO ACTIVE MEMBERSHIP

Jacobus George Bursch, Caracas, Venezuela, S. A.
J. W. Butler, Jr., Hans E. Thalmann, Wolf Maync
Lawrence Wilford Curtis, Oklahoma City, Okla.
Harold J. Kleen, Don L. Hyatt, Roy D. McAninch
Hollis Blair Fender, Bloomington, Ind.
Carl B. Anderson, Ralph E. Esarey, L. A. Mylius
Vincent Eugene Hanes, Midland, Tex.
H. A. Hemphill, L. Wayne Ashmore, John T. Rouse
Richard Walter Harding, Bradford, Pa.
W. H. Young, Jr., C. D. Whorton, E. T. Heck

Benjamin Herbert Martin, Abilene, Tex.
James R. Day, Frank B. Conselman, G. H. Brodie
John Edmund McCall, New Orleans, La.
James H. Todd, H. N. Hickey, L. I. Brown
Charles Vaughn Roberts, Jr., Corpus Christi, Tex.
J. S. Dismukes, H. D. McCallum, Cleo E. Buck
Pat Kennedy Sutherland, Bartlesville, Okla.
W. W. Mallory, Charles E. Decker, J. K. Knox

NEW ROCK-COLOR CHART—REPORT ON DISTRIBUTION[1]

RONALD K. DeFORD[2]
Austin, Texas

The new rock-color chart, which the Association helped to design and publish, has been on sale for more than a year. It has been well received by the geologic profession, both in the United States and abroad.

E. N. Goddard, chairman of the Rock-Color Chart committee, reports that on July 15, 1949, one year after the chart was first put on sale, 946 charts had been sold by the National Research Council and 11 complimentary copies had been distributed. In addition, the United States Geological Survey had distributed 464 copies to its geologists, making a total of 1421 charts in use at the end of the first year. Many of those sold by the National Research Council have gone to oil companies and to universities and colleges.

One hundred thirty-six charts have gone to foreign countries, listed as follows.

Africa	2	Federation of Malaya	1
Alaska	1	Great Britain	9
Algeria	6	Hawaii	2
Argentina	1	Holland	2
Australia	2	India	2
Belgian Congo	4	Mexico	11
Belgium	1	New Zealand	12
Brazil	23	Philippines	1
Canada	19	Poland	1
Chile	1	Russia	2
China	1	Saudi Arabia	3
Colombia	5	Sweden	3
Denmark	4	Venezuela	16
Egypt	1		

At the meetings of the State geologists at San Francisco in February, Joseph T. Singewald, Jr., gave a report on the chart, and a resolution was passed urging all State geological surveys to adopt the use of the chart. The charts sell at $5.50. The Munsell Color Company, Baltimore, Maryland, has contracted to furnish 2,100 charts at $5.00 each. The remaining 50 cents is spent for distribution. Unfortunately, rising labor costs have affected the Munsell Company as well as other businesses, and it finds that the cost of sticking the colors on the charts is greater than anticipated. The company wishes to increase the charge to $6.50 per chart on any future orders. The present stock of charts is probably sufficient to last for about 8 months, but before the end of that time the Rock-Color Chart committee must decide whether to increase the price to $7.00 per chart or to reduce the number of colors shown. Probably the committee will decide to increase the price.

[1] Manuscript received, September 14, 1949.

[2] A.A.P.G. representative on Rock-Color Chart committee, a sub-committee of the committee on Symposium on Sedimentation, Division of Geology and Geography, National Research Council.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1784-1786, 1 FIG.

MEMORIAL

WILLIAM VAN HOLST PELLEKAAN

(1880–1949)

William van Holst Pellekaan died on June 8, 1949. For many months preceding he had been in poor health and the end came during a protracted operation. Funeral services were held at Anaheim, California, and he was laid to rest in Westminster Cemetery in Orange County, California, on Friday, June 10.

He is survived by his wife to whom he was married in Dallas on November 23, 1923. A twin brother, Cornelius van Holst Pellekaan, and a niece live in The Hague but no other near relatives survive him.

He was the son of Jacob van Holst Pellekaan and Dorine Ritmeester and was born on May 11, 1880, at Tegal on the island of Java. In 1884 his mother returned to Holland for medical treatment and took him and his brother with her to live in The Hague. It was the custom of those engaged in work in the colonies to have their children educated at home in Holland and when their mother rejoined her husband she left the two boys to be cared for by friends in Leiden where they attended the elementary schools and the first part of the secondary school. After this William entered a preparatory school for military officers at Alkmaar and on completing this training he entered the Military College at Breda and was graduated with a commission in 1901.

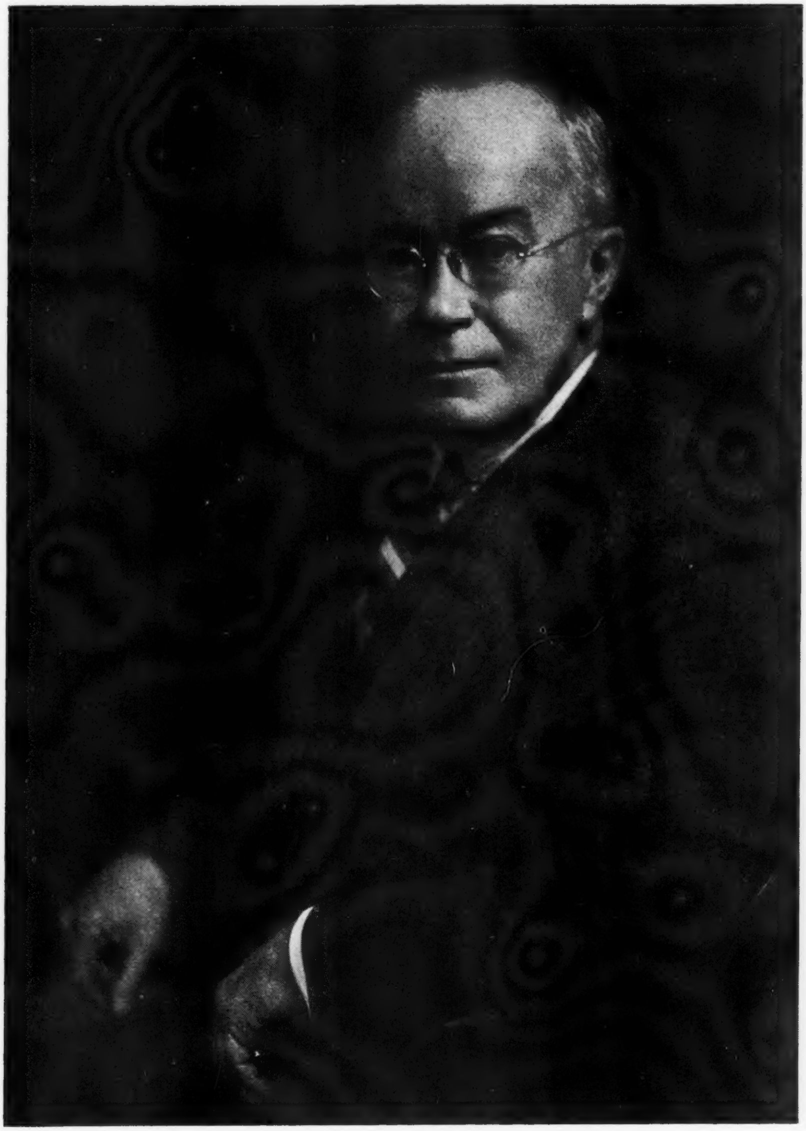
In 1902 he entered the Colonial Indian Army of the Netherlands East Indies and he served in North Sumatra until 1908, carrying on the customary duties of an officer of the Colonial Army. On some of his missions he penetrated parts of the jungle never before reached by a European and often this sort of duty involved him in fighting with hostile natives, some of whom were fanatics. On one occasion, while unarmed and writing in his temporary headquarters, he sent his orderly for a cup of coffee and as the soldier disappeared a native who had been awaiting this opportunity sprang from his hiding place and attacked him with a bolo. Fortunately the orderly was not out of hearing and, hastily returning, he shot the intruder and van Holst escaped death though severely wounded. On another occasion he was fired on from ambush but again he escaped though with severe wounds in the chest and scalp.

At various times he was in command of troops detailed to protect geological parties of the Bataafsche Petroleum Maatschappij from unfriendly natives and in this way he became acquainted with geologists and acquired a great interest in the work they were doing.

In the year 1908 he was sent to the Island of Nias where fighting was going on and during a serious encounter he was so severely wounded by a bolo cut in the thigh that he was incapacitated for many months. The wound was badly infected and the surgeons finally informed him that in order to save his life they would have to amputate the leg. He refused the operation and eventually recovered though only after 6 months in the hospital. Those who recall something of surgical methods before the first World War can imagine the intolerable suffering that van Holst endured during the dressing and treatment of such a wound.

On his recovery he was declared to be physically unfit for any further army service and was discharged from the army and returned to Holland. In Holland he was fortunate enough to find a surgeon who was willing to undertake to repair the muscles of his leg and actually succeeded to a degree that in after years van Holst was able to walk fairly well and only a few people ever suspected that he had had a serious accident.

With the ending of his army career he decided to take up the study of geology and in



William van Holst Pellekaan

1911 he entered the University of Zurich. Here he completed the requirements for the doctorate in geology. His thesis, "The Geology of the Mountain Group of Piz Scopi, Switzerland," gave the results of his studies of metamorphic rocks and attracted some favorable attention at the time. For example, Harker refers to this work in his book on Metamorphism.

In 1913 he entered the service of the Royal Dutch Shell Company and was first sent out to Sumatra and Java where he continued to work until the latter part of 1917, when he was returned to Holland and engaged in work at the head office of the Company in The Hague.

Late in 1918 he was sent out again, this time to the Shell Company of California. Here he served as chief geologist until July, 1922. His work in California was interrupted by an 8 months trip to Peru in 1920 and by a 6 months expedition to Ecuador in 1921.

After a brief vacation in Holland he returned again to the United States in September, 1922, as chief geologist of the Roxana Petroleum Company (later the Shell Petroleum Corporation) with headquarters in St. Louis. This position he held until April, 1928, when he was appointed vice-president of the Shell Petroleum Corporation in charge of exploration. On December 31, 1938, he retired from company work and after a few months went to California and made his home in Beverly Hills where he lived to the time of his death.

Coming to the United States, as he did, during the initial stages of the existence of the Shell Companies, he was influential in shaping the exploration policies of those companies. A large number of the senior members of the Shell geological staff worked directly under him at one time or another and all of these men will remember well the diligent manner in which he carried on the search for new oil fields. Probably because of his intense interest in exploration problems there seemed to be no limit to his working power. When field work was delayed by heavy rain, snow, or other causes, the party usually took the opportunity of relaxing. It would finally be noticed that "Doc" had quietly disappeared and he could usually be found in his room working on his reports or searching the literature for facts which might aid him in understanding the region in which he was working.

As is common with most well educated men of his nationality he could easily read and speak German, French, and English as well as Dutch. In addition, he spoke Malay and during his journeys to South America he learned to speak and read Spanish.

His wide knowledge of the literature, both American and European, his years of experience in many oil regions, coupled with an alert mind, made his inspection trips most stimulating and inspiring for his assistants. He was successful in his work and many oil properties came to the Shell as a result of his efforts and the work of the geological organization which he built. Sir Henri Deterding once told him that his presence in an area seemed to produce there "a golden rain."

This man of two entirely different careers remained a soldier to the end. He told his wife that he must go to the hospital for a minor operation and that he would probably be out again in two or three days, and apparently no one else but his physicians had any reason to believe that the operation was a serious one, though it is certain that he himself was only too well aware of what was necessary to be done and knew that the prospects of a successful outcome were slender indeed.

E. Fred Davis

Los Angeles, California
September 8, 1949

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 10 (OCTOBER, 1949), PP. 1787-1790

AT HOME AND ABROAD

NEWS OF THE PROFESSION

RAY E. HURST is in the employ of the Pure Oil Company, Midland, Texas.

JACK WALTON EDWARDS is working for the Apache Exploration Company, Houston, Texas.

FREDERICK A. BURT, after 28 years as associate professor, professor, and acting head of the geology department at Texas A. and M. College, has retired, and is living at 123 Union Street, Bennington, Vermont.

OTIS B. ALLRED is with the Sinclair Oil and Gas Company at Midland, Texas.

G. LESLIE WHIPPLE has moved from the Richmond Exploration Company of Venezuela at Maracaibo, to the Standard Oil Company of Texas, as district geologist of the Texas Panhandle with headquarters at Amarillo, Texas.

HARLAN H. YOAKAM has resigned his position as division geologist with the Plymouth Oil Company, Sinton, Texas, to become a consultant at Sinton.

E. W. FORT, recently exploration engineer with the Shell Oil Company, Inc., at New Orleans, has joined the firm of Meyer and Achtschin, consultants, at Dallas, Texas.

CHARLES W. WILSON, JR., professor of geology at Vanderbilt University, is the author of the new *Bulletin 56* of the Tennessee Division of Geology, "Pre-Chattanooga Stratigraphy in Central Tennessee." It contains 407 pages, 89 figures, and 28 plates. The address of the State geologist, H. B. BURWELL, is G-5 State Office Building, Nashville 3, Tennessee. The price is $2.65.

The Kansas Geological Society opened the fall season with the following program: "Pleistocene Geology of Kansas," by JOHN C. FRYE; "Physiographic Divisions in Kansas," by WALTER SCHOEWE; "Structural Movements on a Line from Smith County to Mead County," by WALLACE LEE. This morning meeting was held on September 17 at the University of Kansas, at Lawrence, after which there was time to visit the new building which houses the University department of geology, before the football game in the afternoon, between the University of Kansas and Texas Christian University, Fort Worth.

EMILE ROD, formerly with the Venezuela Atlantic Refining Company in Caracas, Venezuela, is with Cia. Petrolera de Peten S. A., Guatemala, C. A.

LEROY WOOLLETT has returned to the University of Texas at Austin, for his Master's degree in geology, having concluded a training period in West Texas with the Magnolia Petroleum Company.

F. C. SEALEY is with the California Texas Oil Company, Limited, 551 Fifth Avenue, New York City.

CHARLES B. NEWMARCH has changed his business connection from the British Columbia Department of Mines to the Crow's Nest Pass Coal Company, Limited, Fernie, British Columbia.

GLEN PETRICK is district geologist for the American Republics Corporation at San Antonio, Texas. He was recently with the Transwestern Royalty Corporation.

GEORGES VORBE, who has been with the department of petroleum engineering at the New Mexico School of Mines, has joined the firm of D. D. Feldman Oil and Gas, Dallas, Texas.

RALPH B. CANTRELL, practicing independently in geology and petroleum production, is situated at 2519 Gulf Building, Houston, Texas.

R. F. WEICHERT has changed his connection from Imperial Oil Limited, Toronto, to Carter Oil Company, Tulsa, Oklahoma.

ROY HARRIS is with the Lion Oil Company at Midland, Texas.

W. D. ANDERSON is now associated with the firm of W. D. Anderson & Sons, Midland Tower Building, Midland, Texas. The other firm members are Paul D. Anderson and Payton V. Anderson.

CHESTER RAY LONGWELL is editor and JOHN RODGERS is assistant editor of the *American Journal of Science* published at New Haven, Connecticut. Richard S. Lull has relinquished his editorship after 16½ years of service in that capacity.

JOHN F. MANN, JR., is with the Illinois State Geological Survey Division.

H. P. SCHAUB has left Stanford University. He may be addressed in care of the Bataafsche Petroleum Mij., 30 Carel van Bylandtlaan, The Hague, Netherlands.

D. STAEGER, of Bern, Switzerland, is with the N. V. de Bataafsche Petroleum Mij., Pladjoe, Sumatra.

CONRAD O. HAGE is in the employ of the Barnsdall Oil Company, Calgary, Alberta.

W. C. CLARK is with the Reliable Geophysical Company at Yoakum, Texas.

G. E. ARCHIE, of the Shell Oil Company, was the speaker at the Houston Geological Society meeting, September 12. His subject was "Petrophysics."

B. W. BEEBE, exploration manager of the Anderson-Prichard Oil Corporation, Oklahoma City, spoke on "Geologic Responsibility in Seismic Exploration," at the meeting of the South Texas Geological Society, San Antonio, September 15.

The Pacific Section Geological Forum, held in Los Angeles, September 19, presented the following program: WALTER D. ABEL, petroleum and mining engineer, State of California Corporation Commission, "Geological Reports, Fact or Fiction?"; PAUL CASAMAJOR, Fairchild Aerial Surveys, Inc., "Some Aspects of Aerial Photography"; FRANK PARKER, geologist, Signal Oil and Gas Company, "Report on Powder River Basin, Wyoming Field Trip."

CHARLES G. ALLEN has been transferred from the exploration department of the Standard Oil Company of California at Taft to the Richmond Petroleum Company of Colombia, Bogota.

CHARLES J. CROWLEY, who was employed by the New Mexico Natural Gas Company, is a geological scout for the Ohio Oil Company at Lewistown, Montana.

D. J. DOEGLAS, of the Landbouevhoogeschool, Wageningen, Netherlands, will be at the School of Geology of the Louisiana State University in Baton Rouge, Louisiana, as visiting professor in geology and sedimentary petrology, until June, 1950.

P. K. SUTHERLAND, after completing a series of field seasons in northeast British Columbia for the Phillips Petroleum Company, has taken a year's leave of absence. He sailed from New York, September 21, on the *Queen Elizabeth* to do graduate research in paleontology and stratigraphy at Cambridge. His address will be: Emmanuel College, Cambridge University, England.

WAYNE MOORE FELTS has left the Houston office of The Texas Company where he was doing research in subsurface stratigraphy to accept an associate professorship in geology at Pennsylvania State College, State College, Pennsylvania. Felts has recently been appointed director of the Pennsylvania State College School of Mineral Industries summer field camp.

J. E. BRANTLY, president of the Drilling and Exploration Company, Dallas, Texas, is the author of an article in the September issue *World Petroleum* (New York), entitled "Improvement in World Economy Rests on Oil."

O. J. LILLY has changed his connections from Byrd-Frost, Inc., at Durango, Colorado, to the Southern Union Production Company, at Farmington, New Mexico.

KARL M. BUEHLER resigned from the J. M. Huber Corporation, and effective October 1, he became a partner with Joe Guyer in the Denver Sample Log Service, Denver, Colorado.

PHILIP A. CHENOWETH is in the department of geology at Amherst College, Amherst, Massachusetts.

ROBERT E. WILLS, JR., recently with the Magnolia Petroleum Company at Houston, Texas, is in the geology department at the University of Kansas, Lawrence, Kansas.

W. T. PRICKETT is in the employ of the Stanolind Oil Company, Littlefield, Texas.

LEROY E. BECKER, formerly with the Creole Petroleum Corporation, Jusepin, Venezuela, is now at Maracaibo.

After spending the summer in field instruction at the University of Oklahoma summer camp near Florence, Colorado, KEITH M. HUSSEY has moved to Ames, Iowa, to teach in the geology department of the Iowa State College.

Lieutenant ROY E. HANSON, recently with the Shell Oil Company, Inc., Wichita Falls, is serving on extended active duty with the United States Air Forces at Maxwell AF Base, Alabama.

PIERRE FREYMOND has left Lausanne, Switzerland. He is in the employ of the Shell Caribbean Petroleum Company, Maracaibo, Venezuela.

STANLEY P. FISHER, formerly at Rutgers University, New Brunswick, New Jersey, is in the department of geology at Cornell University, Ithaca, New York.

A meeting of the Rocky Mountain Section, American Society of Photogrammetry, was held in Denver, October 3–4. Among the speakers scheduled were: A. R. WASEM, Geophoto Services; BENJAMIN A. TATOR, Louisiana State University; CHARLES READ, United States Geological Survey; JEAN HITTLE, Bureau of Reclamation. LAURENCE BRUNDALL, Geophoto Services, Denver, was convention chairman.

A regional exploration meeting of the Society of Exploration Geophysicists will be held in Dallas, November 17 and 18, 1949. The meeting is being sponsored jointly by the

local geophysical societies of Dallas, Fort Worth, Tulsa, and Shreveport. The Adolphus Hotel is headquarters.

President C. W. TOMLINSON's speaking schedule for the last half of his term of office follows. This completes his visits to A.A.P.G. affiliated societies and related geological groups.

September	19, 1949	Fort Worth Geological Society, Fort Worth, Texas
	20	North Texas Geological Society, Wichita Falls
	21	Panhandle Geological Society, Amarillo, Texas
	22	Geologists at Enid, Oklahoma, and Phillips University
	29	Shawnee Geological Society, Shawnee, Oklahoma
October	3	Tulsa Geological Society, Tulsa, Oklahoma
	4	Rocky Mountain Association of Geologists, Denver, Colorado
	6	Petroleum Division, A.I.M.E., San Antonio, Texas
	12–15	A.A.P.G. Regional Meeting, Biloxi, Mississippi
	18	Indiana-Kentucky Geological Society, Evansville, Indiana
	19	Illinois Geological Society, probably at Mt. Vernon
	20	University of Illinois, Urbana
	25	Pittsburgh Geological Society, Pittsburgh, Pennsylvania
	26	Washington Geological Society, Washington, D. C.
	27	A.A.P.G. Eastern Division, New York City
	28	Appalachian Geological Society, Charleston, West Virginia
November	10–12	G.S.A. Convention, El Paso, Texas
	13–14	A.A.P.G. Executive Committee meeting, El Paso, Texas
	17–18	A.A.P.G. Pacific Section, Los Angeles, California
	21	San Joaquin Geological Society, Bakersfield, California
	22	A.A.P.G. membership at San Francisco, California
	23	Intermountain Society of Petroleum Geologists, Salt Lake City, Utah
	25	Wyoming Geological Society, Casper
January	12–13, 1950	A.A.P.G. Regional Meeting, Oklahoma City, Oklahoma
	18	Asociacion Venezolana de Geologia, Mineria, y Petroleo, Caracas, Venezuela
	19 or 20	A.A.P.G. membership at Maracaibo, Venezuela
	23	Instituto Colombiano de Petroleo, Bogota, Colombia

WELDON W. RAU, assistant professor of geology at the College of Puget Sound, has been granted a semester's leave of absence in order to complete work on his doctorate at the University of Iowa. In addition to study and research at the Iowa institution he will also hold the rank of instructor on the university's teaching staff.

W. L. HORNER, chief engineer, Barnsdall Oil Company, Tulsa, was a featured speaker at the 20th anniversary meeting of the Independent Petroleum Association in Fort Worth, October 3–4. His paper is "Increased Oil Recovery by Means of Water Injection Pressure Maintenance."

SOUTH TEXAS GEOLOGICAL SOCIETY ANNUAL MEETING, SAN ANTONIO, OCTOBER 28–30

The 16th annual meeting and field trip of the South Texas Geological Society will be held in San Antonio, October 27–30, 1949. The Plaza Hotel, San Antonio, will be the headquarters for the meeting. Registration will begin on Thursday evening, October 27, and continue, Friday morning, October 28, in the hotel lobby. Morning and afternoon technical sessions will be held on Friday, October 28, in the Plaza Ball Room on the Mezzanine Floor. Luncheon will be served in the Ball Room from 12:00 to 1:00, October 28. An informal dinner dance will be held at Club Seven Oaks following the technical sessions on Friday, October 28. A 2-day field trip to study Cretaceous outcrops in the area west of San Antonio is scheduled for Saturday and Sunday, October 29 and 30. Arrangements have been made to stay at the Hotel Roswell in Del Rio on Saturday night. Personal cars will be used for transportation. M. E. FORNEY, 804 Alamo National Building, San Antonio 5, Texas, is general chairman.

GEOLOGICAL AND GEOPHYSICAL SOCIETIES

THE SOCIETY OF EXPLORATION GEOPHYSICISTS

President - - - - - - Andrew J. Gilmour
Amerada Petroleum Corporation
Box 2040, Tulsa, Oklahoma

Vice-President - - - - - George E. Wagoner
Carter Oil Company
Shreveport, Louisiana

Editor - - - - - - - - - - R. A. Geyer
Humble Oil and Refining Company
Houston, Texas

Secretary-Treasurer - - - - - - K. E. Burg
Geophysical Service, Inc.
6000 Lemmon Ave., Dallas, Texas

Past-President - - - - - - L. L. Nettleton
Gravity Meter Exploration Co.
1348 Esperson Bldg., Houston, Tex.

Business Manager - - - - - Colin C. Campbell
Room 210, 817 South Boulder, Tulsa, Oklahoma
P.O. Box 1614

CALIFORNIA

PACIFIC SECTION AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

President - - - - - - - Clifton W. Johnson
Richfield Oil Corporation
Room 430, Richfield Bldg.
Los Angeles 13, California

Vice-President - - - - - - John E. Kilkenny
Chanslor-Canfield Midway Oil Company
4549 Produce Plaza West, Los Angeles 11

Secretary-Treasurer - - - - - Harold E. Rader
Standard Oil Company, Box 2437, Terminal Annex
Los Angeles 54

Monthly meetings. Visiting geologists are welcome.

CALIFORNIA

SAN JOAQUIN GEOLOGICAL SOCIETY

BAKERSFIELD, CALIFORNIA

President - - - - - - Robert B. Hutcheson
The Superior Oil Company, Box 1031

Vice-President - - - - - Floyd L. Johnson
Honolulu Oil Corporation

Secretary-Treasurer - - - Maxwell G. Caben
Seaboard Oil Company of Delaware, Box 7

Dinner meetings on 2d Tuesday of each month or as announced, El Tejon Hotel, Bakersfield.

COLORADO

ROCKY MOUNTAIN ASSOCIATION OF GEOLOGISTS

DENVER, COLORADO

President - - - - - - - - - Dart Wantland
U. S. Reclamation Service

1st Vice-President - - - - - S. W. Lohman
U. S. Geological Survey
136 New Customhouse

2d Vice-President - - - - - - E. W. Scudder
J. M. Huber Corporation
Box 2098

Secretary-Treasurer - - - - - Kenneth L. Gow
Superior Oil Company of California
506 First National Bank Building

Evening dinner (6:30) and technical program (8:00) first Tuesday each month or by announcement.

FLORIDA

SOUTHEASTERN GEOLOGICAL SOCIETY

Box 841
TALLAHASSEE, FLORIDA

President - - - - - - - - - W. C. Blackburn
Humble Oil and Refining Company, Box 506

Secretary-Treasurer - - - - - Albert A. Raasch
Humble Oil and Refining Company,
Box 506

Meetings will be announced. Visiting geologists and friends are welcome.

ILLINOIS

ILLINOIS GEOLOGICAL SOCIETY

President - - - - - - - - - - - C. E. Brehm
C. E. Brehm Drilling & Producing
Mt. Vernon

Vice-President - - - - - - - - Joseph Neely
Magnolia Petroleum Company
Box 535, Mt. Vernon

Secretary-Treasurer - - - - - Lloyd A. Harris
Carter Oil Company, Box 568, Mattoon

Meetings will be announced.

INDIANA-KENTUCKY

INDIANA-KENTUCKY GEOLOGICAL SOCIETY

EVANSVILLE, INDIANA

President - - - - - - - H. W. Bodkin
Superior Oil Company

Vice-President - - - - - - - D. G. Sutton
Sun Oil Company, Box 717

Secretary-Treasurer - - - - - J. B. Vaughan
Ashland Oil and Refining Company
Henderson, Kentucky

Meetings will be announced.

KANSAS

KANSAS GEOLOGICAL SOCIETY

WICHITA, KANSAS

President - - - - - - - - Don W. Payne
Sinclair Prairie Oil Company

Vice-President - - - - - - - T. G. Wright
Stanolind Oil and Gas Company

Secretary-Treasurer - - - - Victor F. Reiserer
Superior Oil Company, 510 K.F.H. Bldg.

Regular Meetings: 7:30 P.M., Geological Room, University of Wichita, first Tuesday of each month. Noon luncheons, first and third Monday of each month at Wolf's Cafeteria. The Society sponsors the Kansas Well Log Bureau, and the Kansas Well Sample Bureau, 508 East Murdock. Visiting geologists and friends welcome.

LOUISIANA

NEW ORLEANS GEOLOGICAL SOCIETY
NEW ORLEANS, LOUISIANA

President - - - - - - - - - Fred S. Goerner
California Company, 1818 Canal Building
Vice-President and Program Chairman - - - - - - - - - - - - - - - M. N. Broughton
The Texas Company, 1500 Canal Building
Secretary-Treasurer - - - - - H. A. Nystrom
Schlumberger Well Surveying Corporation
452 Canal Building

Meets the first Monday of every month, October-May, inclusive, 12 noon, St. Charles Hotel. Special meetings by announcement. Visiting geologists cordially invited.

THE SHREVEPORT GEOLOGICAL SOCIETY
SHREVEPORT, LOUISIANA

President - - - - - - - - Victor P. Grage
Consultant, 415 Ardis Building
Vice-President - - - - - - - R. T. Wade
Schlumberger Well Surveying Corporation
Box 92
Secretary-Treasurer - - - - Charles A. Hickcox
Centenary College, Box 750

Meets monthly, September to May, inclusive, in the State Exhibit Building, Fair Grounds. All meetings by announcement.

LOUISIANA

SOUTH LOUISIANA GEOLOGICAL SOCIETY
LAKE CHARLES, LOUISIANA

President - - - - - - - - - W. B. Neill
Stanolind Oil and Gas Company
Vice-President - - - - - - - Pete Haberstick
Atlantic Refining Company
Secretary - - - - - - - James M. Whatley
Union Sulphur Company
Treasurer - - - - - - - - - Bert C. Timm
Magnolia Petroleum Company

Meetings: Dinner and business meetings third Tuesday of each month at 7:00 P.M. at the Majestic Hotel. Special meetings by announcement. Visiting geologists are welcome.

MICHIGAN

MICHIGAN GEOLOGICAL SOCIETY
MOUNT PLEASANT, MICHIGAN

President - - - - - - - - Glenn C. Sleight
Sun Oil Company, Taylor Building
Vice-President - - - - - - Manley Osgood, Jr.
Consultant, 502 S. Arnold St.
Secretary-Treasurer - - - - - - Jack Mortenson
Sohio Oil Company, 601 S. Main St.
Business Manager - - - Kenneth G. Walsworth
Dept. Conservation, Box 176

Meetings: Monthly, November through May, at Michigan State College, East Lansing, Michigan. Informal dinners at 6:30 P.M. Papers follow dinner. Visitors welcome.

MISSISSIPPI

MISSISSIPPI GEOLOGICAL SOCIETY
BOX 2253, WEST JACKSON, MISSISSIPPI

President - - - - - - - - - E. T. Monsour
Consultant, Box 2571, West Jackson
Vice-President - - - - - - - Charles E. Buck
Skelly Oil Company, 100 East Pearl Building
Treasurer - - - - - - - - - W. H. Knight
Union Producing Company
Secretary - - - - - - - - - - F. T. Holden
Carter Oil Company, Box 1490

Meetings: First and third Thursdays of each month, from October to May, inclusive, at 7:30 P.M., the Edwards Hotel, Jackson, Mississippi. Visiting geologists welcome to all meetings.

NEW YORK

EASTERN SECTION AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
NEW YORK, NEW YORK

President - - - - - - - - Hollis D. Hedberg
Gulf Oil Corp., 17 Battery Place
Vice-President - - - - - - Douglas A. Greig
Standard Oil Co., (N.J.), 30 Rockefeller Plaza
Treasurer - - - - - - - - - - Marshall Kay
Department of Geology, Columbia University
Secretary - - - - - - Godfrey F. Kaufmann
Standard-Vacuum Oil Co., 26 Broadway,
Room 1556

Meetings by announcement to members. Visiting geologists and friends cordially invited.

OKLAHOMA

ARDMORE GEOLOGICAL SOCIETY
ARDMORE, OKLAHOMA

President - - - - - - - - - I. Curtis Hicks
Phillips Petroleum Company
Vice-President - - - - - - Earl Westmoreland
Seaboard Oil Company
Secretary-Treasurer - - - - - - Frank Millard
Schlumberger Well Surveying Corp., Box 747

Dinner meetings will be held at 7:00 P.M. on the first Wednesday of every month from October to May, inclusive, at the Ardmore Hotel.

OKLAHOMA CITY GEOLOGICAL SOCIETY
OKLAHOMA CITY, OKLAHOMA

President - - - - - - - - - - Rizer Everett
Carter Oil Company
Vice-President - - - - - - Richard L. Roberts
Vickers Petroleum Company
Secretary - - - - - - - - - - L. W. Curtis
Sohio Petroleum Company
Treasurer - - - - - - - - - Joseph M. Sears
Independent

Meetings: Technical program each month, subject to call by Program Committee, Oklahoma City University, 24th Street and Blackwelder. Luncheons: Every second and fourth Thursday of each month, at 12:00 noon, Y.W.C.A.

OKLAHOMA

SHAWNEE GEOLOGICAL SOCIETY
SHAWNEE, OKLAHOMA

President - - - - - - - - Doyle M. Burke
The Texas Company, Box 1007

Vice-President - - - - - - - Jack W. Davies
Halliburton Oil Well Cementing Company

Secretary-Treasurer - - - - Marcelle Mousley
Atlantic Refining Company, Box 169

Meets the third Thursday of each month at 8:00 P.M., at the Aldridge Hotel. Visiting geologists welcome.

TULSA GEOLOGICAL SOCIETY
TULSA, OKLAHOMA

President - - - - - - - - - - L. H. Lukert
The Texas Company, Box 2420

1st Vice-President - - - - - Daniel A. Busch
Carter Oil Company, Box 801

2d Vice-President - - - - John M. Nash
Shell Oil Company, Box 1191

Secretary-Treasurer - - - - Mary Whitehead
Stanolind Oil and Gas Company, Box 591

Editor - - - - - - - Oscar E. Wagner, Jr.
Mid-Continent Petroleum Corporation, Box 381

Business Manager, Digest - - - - V. L. Frost
Ohio Oil Company, Thompson Building

Meetings: First and third Mondays, each month, from October to May, inclusive, at 8:00 P.M., University of Tulsa, Lorton Hall. Luncheons: Every Friday (October-May), Chamber of Commerce Building.

PENNSYLVANIA

PITTSBURGH GEOLOGICAL SOCIETY
PITTSBURGH, PENNSYLVANIA

President - - - - - - - Charles F. Bassett
Gulf Oil Corporation, Box 1166

Vice-President - - - - - - - R. E. Sherrill
University of Pittsburgh

Secretary - - - - - - - - - C. E. Prouty
University of Pittsburgh

Treasurer - - - - - - - - Sidney S. Galpin
Peoples Natural Gas Company
545 William Penn Place

Meetings held each month, except during the summer. All meetings and other activities by special announcement.

TEXAS

ABILENE GEOLOGICAL SOCIETY
ABILENE, TEXAS

President - - - - - - - - - - - J. R. Day
Pan American Production Company

Vice-President - - - - - David M. Grubbs
Drilling and Exploration Company

Secretary-Treasurer - - - - - C. S. Noland
Skelly Oil Company

Meetings: 2d Thursday of each month, 7:30 P.M., Wooten Hotel.

TEXAS

CORPUS CHRISTI GEOLOGICAL SOCIETY
CORPUS CHRISTI, TEXAS

President - - - - - - - - - James D. Burke
Seaboard Oil Company of Delaware, Box 601

Vice-President - - - - - W. H. Wallace, Jr.
La Gloria Corporation, Driscoll Building

Secretary-Treasurer - - - - H. W. Volk, Jr.
Tide Water Associated Oil Company
Driscoll Building

Regular luncheons, every Thursday, Terrace Annex Room, Robert Driscoll Hotel, 12:00. Special night meetings by announcement.

DALLAS GEOLOGICAL SOCIETY
DALLAS, TEXAS

President - - - - - - - - - John T. Rouse
Magnolia Petroleum Company
P.O. Box 900

Vice-President - - - - - - - H. V. Tygrett
The Atlantic Refining Company
P.O. Box 2819

Secretary-Treasurer - - - - Gilbert P. Moore
Consulting, 501 Continental Building

Executive Committee - - - - - Edgar Kraus
Atlantic Refining Company
Box 2819

Meetings: Monthly luncheons and night meetings by announcement.

EAST TEXAS GEOLOGICAL SOCIETY
TYLER, TEXAS

President - - - - - - - - - - G. C. Clark
Stanolind Oil and Gas Company
Box 660

Vice-President - - - - - R. M. Trowbridge
Consultant, 225 Owen Building

Secretary-Treasurer - - - - - Rosella L. Bunch
Shell Oil Company, Inc., Box 2037

Luncheons: Each week, Monday noon, Blackstone Hotel.
Evening meetings and programs will be announced. Visiting geologists and friends are welcome.

FORT WORTH GEOLOGICAL SOCIETY
FORT WORTH, TEXAS

President - - - - - - - - H. C. Vanderpool
Texas Pacific Coal and Oil Company
Box 2110

Vice-President - - - - - - - W. Baxter Boyd
Continental Oil Company
1710 Fair Building

Secretary-Treasurer - - - - Thomas Nichols
Rowan Oil Company
Commercial Standard Building

Meetings: Luncheon at noon, Hotel Texas, first and third Mondays of each month. Visiting geologists and friends are invited and welcome at all meetings.

TEXAS

HOUSTON GEOLOGICAL SOCIETY
HOUSTON, TEXAS

President - - - - - - - - Hershal C. Ferguson
Consultant, 935 Mellie Esperson Building

Vice-President - - - - - - - - - R. R. Rieke
Schlumberger Well Surveying Corporation

Secretary - - - - - - - - - James H. McGuirt
Tide Water Associated Oil Company

Treasurer - - - - - - - - - - Marjorie Fuqua
Humble Oil and Refining Company

Regular meeting held the second and fourth Mondays at noon (12 o'clock), Mezzanine floor, Texas State Hotel. For any particulars pertaining to the meetings write or call the secretary.

PANHANDLE GEOLOGICAL SOCIETY
AMARILLO, TEXAS

President - - - - - - - - - G. E. Hatton
Phillips Petroleum Company, Box 1761

Vice-President - - - - - - Robert F. Herron
Oil Development Company, 900 Polk St.

Secretary-Treasurer - - - - - Robert B. Totten
Sun Oil Company, Box 46

Meetings: Luncheon 1st and 3d Wednesdays of each month, 12:00 noon, Herring Hotel. Special night meetings by announcement.

TEXAS

WEST TEXAS GEOLOGICAL SOCIETY
MIDLAND, TEXAS
Box 1595

President - - - - - - - - - W. T. Schneider
Honolulu Oil Corporation, Box 1391

Vice-President - - - - - Ralph D. Chambers
Continental Oil Company, Box 431

Secretary - - - - - - - - - Jesse A. Rogers
The Texas Company, Box 1270

Treasurer - - - - - - John V. Norman, Jr.
Forest Oil Corporation, Box 1821

Meetings will be announced.

WEST VIRGINIA

APPALACHIAN GEOLOGICAL SOCIETY
CHARLESTON, WEST VIRGINIA
P.O. Box 2605

President - - - - - - - - - W. B. Maxwell
United Fuel Gas Company, Box 1273

Vice-President - - - - - - - - John Galpin
1901 Kanawha Valley Building

Associate Vice-President - - - H. P. McJunkin
McJunkin Supply Company

Secretary-Treasurer - - - - W. T. Ziebold
Spartan Gas Company, Box 766

Editor - - - - - - - F. Seigal Workman, Jr.
Acme Engineering Services, Box 923

Meetings: Second Monday, each month, except June, July and August, at 6:30 P.M., Daniel Boone Hotel.

NORTH TEXAS GEOLOGICAL SOCIETY
WICHITA FALLS, TEXAS

President - - - - - - - Joseph W. McDonald
Shell Oil Company, Inc., Box 2010

Vice-President - - - - - Ralph H. McKinlay
Panhandle Producing and Refining Company
Box 1191

Secretary-Treasurer - - - - Walter L. Ammon
Stanolind Oil and Gas Company
Box 1680

Meetings: Luncheon 1st and 3d Thursdays of each month, 12:00 noon, Texas Room, Holt Hotel. Evening meetings by special announcement. Visiting geologists and friends are cordially invited to all meetings.

SOUTH TEXAS GEOLOGICAL SOCIETY
SAN ANTONIO, TEXAS

President - - - - - - - - - - Paul B. Hinyard
Shell Oil Company
2000 Alamo National Building

Vice-President - - - - - - - - J. Boyd Best
Ohio Oil Company

Secretary-Treasurer - - - Louis H. Haring, Jr.
Stanolind Oil and Gas Company

Meetings: One regular meeting each month in San Antonio. Luncheon every Monday noon at Milam Cafeteria, San Antonio.

UTAH

UTAH GEOLOGICAL SOCIETY
SALT LAKE CITY, UTAH
P.O. Box 1015

President - - - - - - - - J. Stewart Williams
Utah State Agricultural College, Logan

Vice-President - - - - - - A. Lee Christensen
Utah Construction Company, Salt Lake City

Corresponding Secretary - - - - Reed F. Welch
American Smelting and Refining Co., Salt Lake City

Recording Secretary - - - - - - - Max Erickson
University of Utah, Salt Lake City

Treasurer - - - - - - - - F. W. Christiansen
University of Utah, Salt Lake City

Sponsors an annual field trip for which a guidebook is published.

Meetings by announcement.

WYOMING

WYOMING GEOLOGICAL ASSOCIATION
CASPER, WYOMING
P.O. Box 545

President - - - - - - - - - Jed B. Maebius
Gulf Oil Corporation, Box 1971

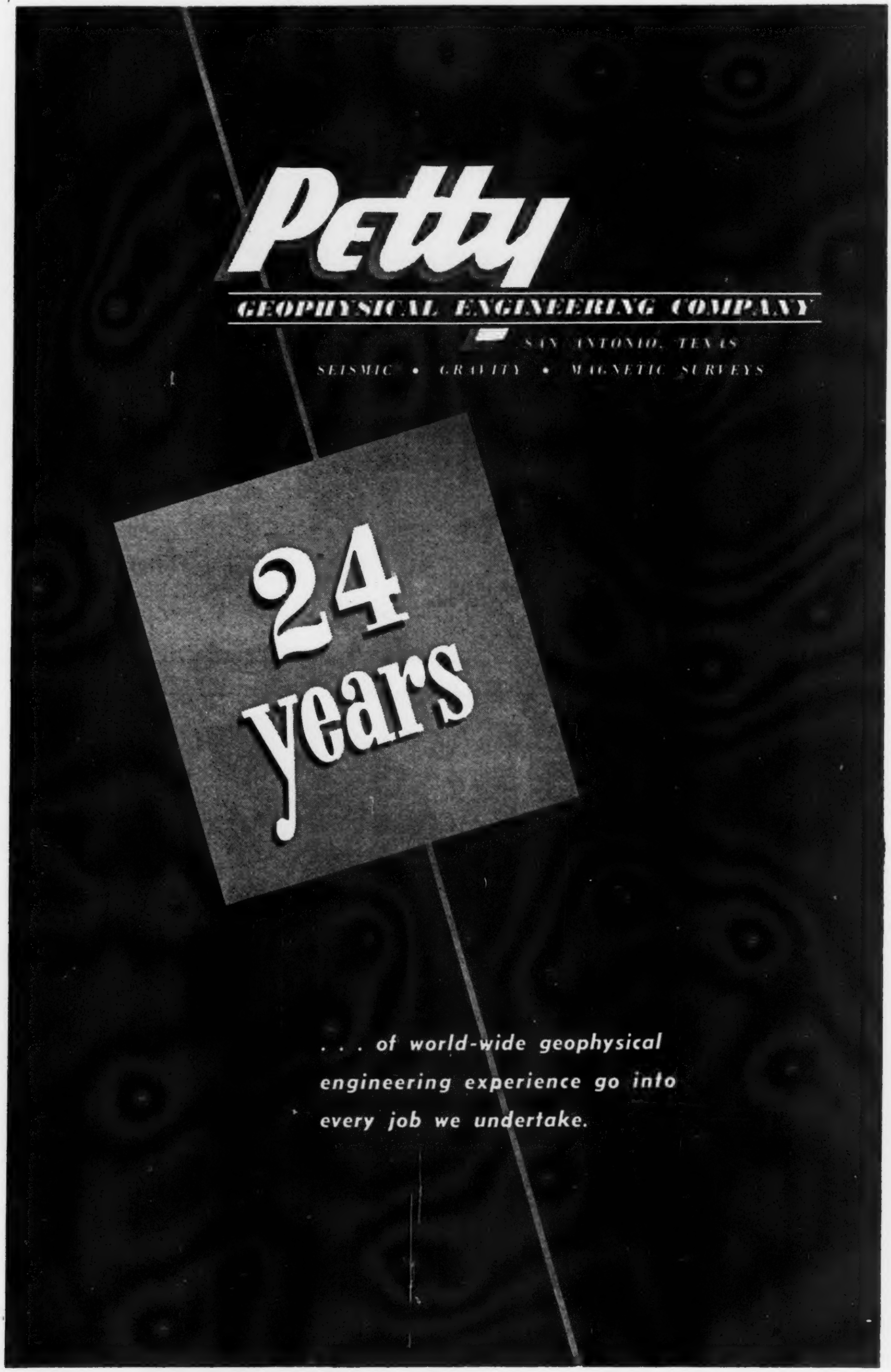
1st Vice-President - - - - Emmett E. Schieck
Morton Oil Company, Box 1970

2d Vice-President (Programs) - Donald E. Edstrom
British-American Oil Producing Company, Box 620

Secretary - - - - - - - - J. B. Headley, Jr.
Atlantic Refining Company

Treasurer - - - - - - - - - George L. Goodin
Petroleum Information, Inc.

Informal luncheon meetings every Friday, 12 noon, Townsend Hotel. Visiting geologists welcome. Special meetings by announcement.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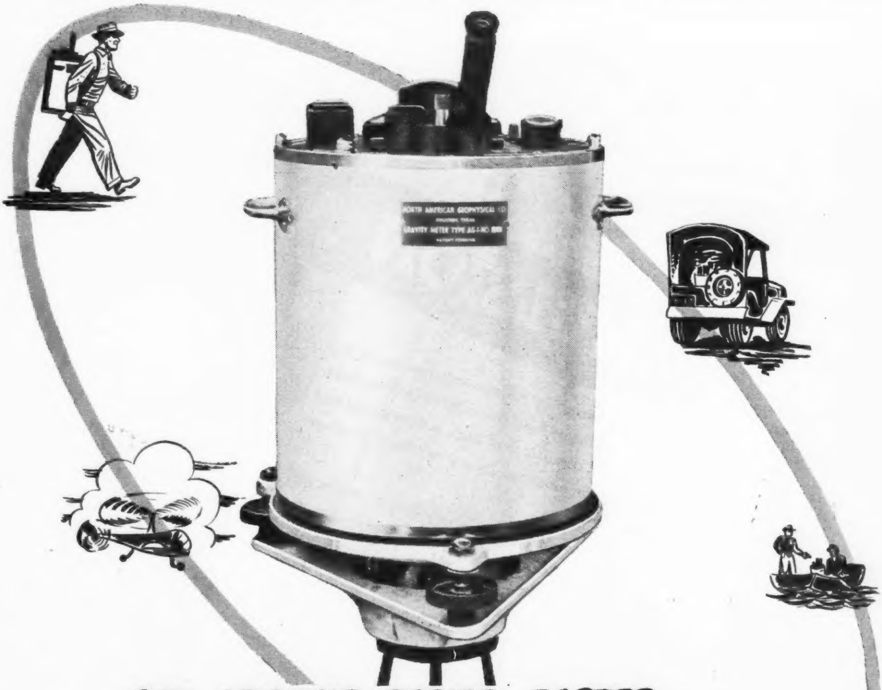

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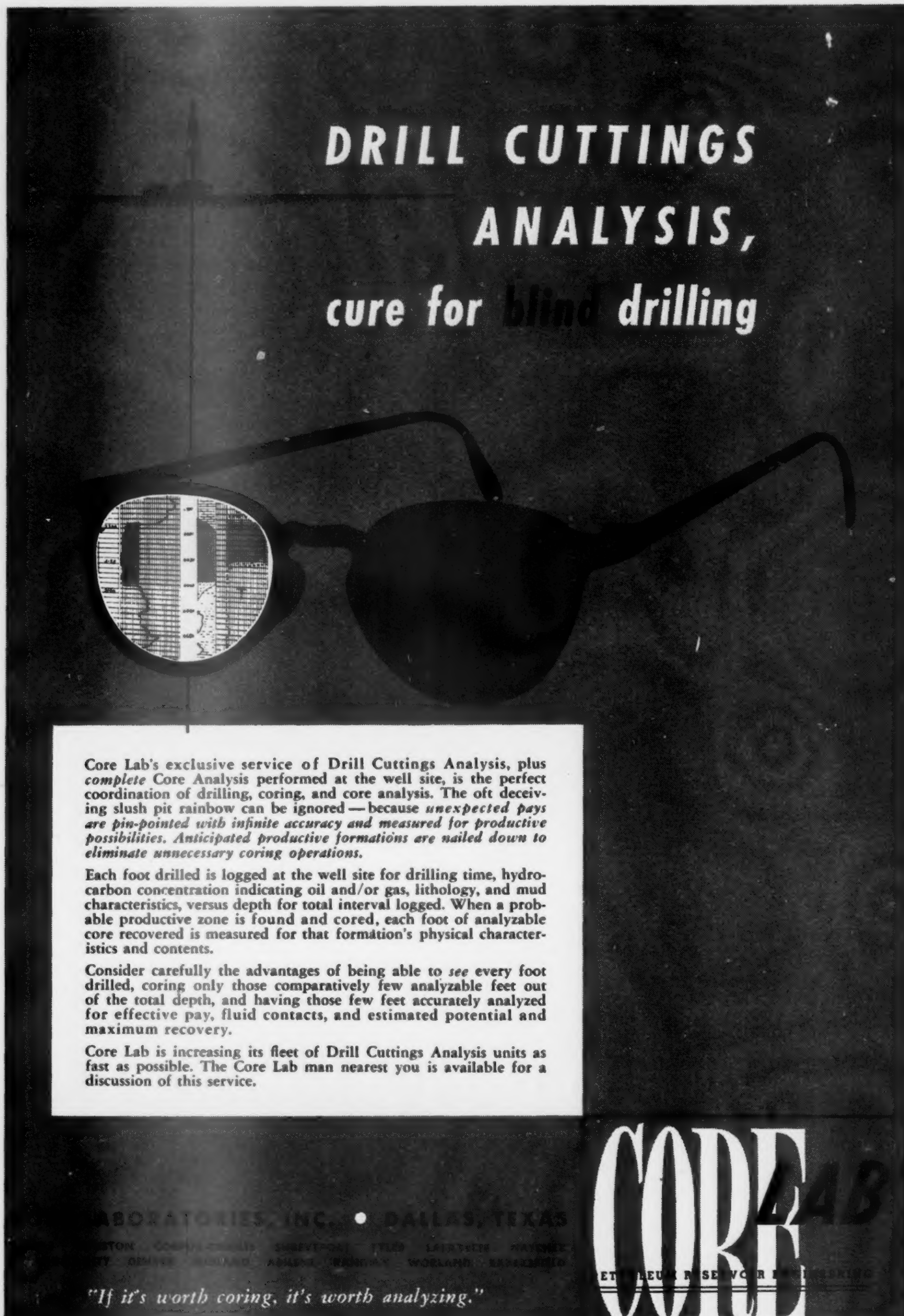

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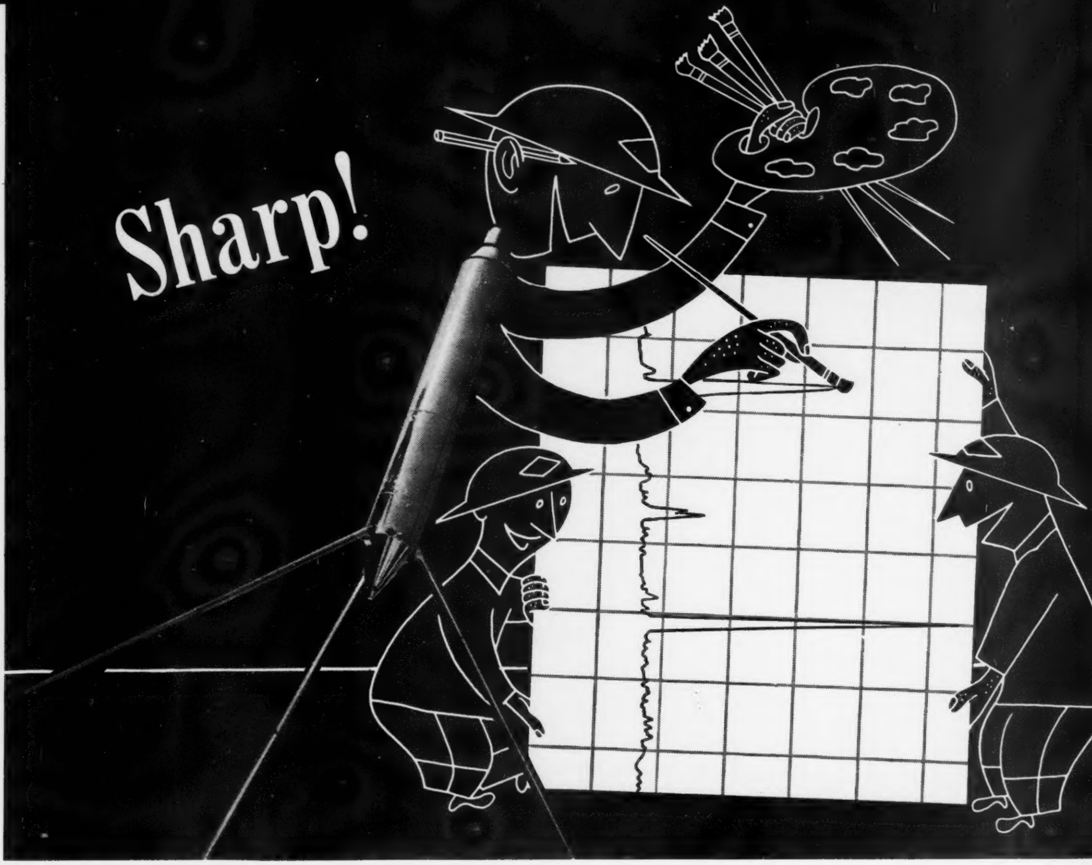

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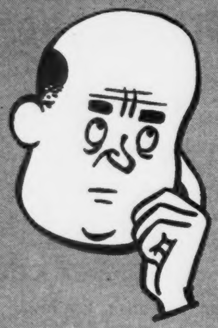


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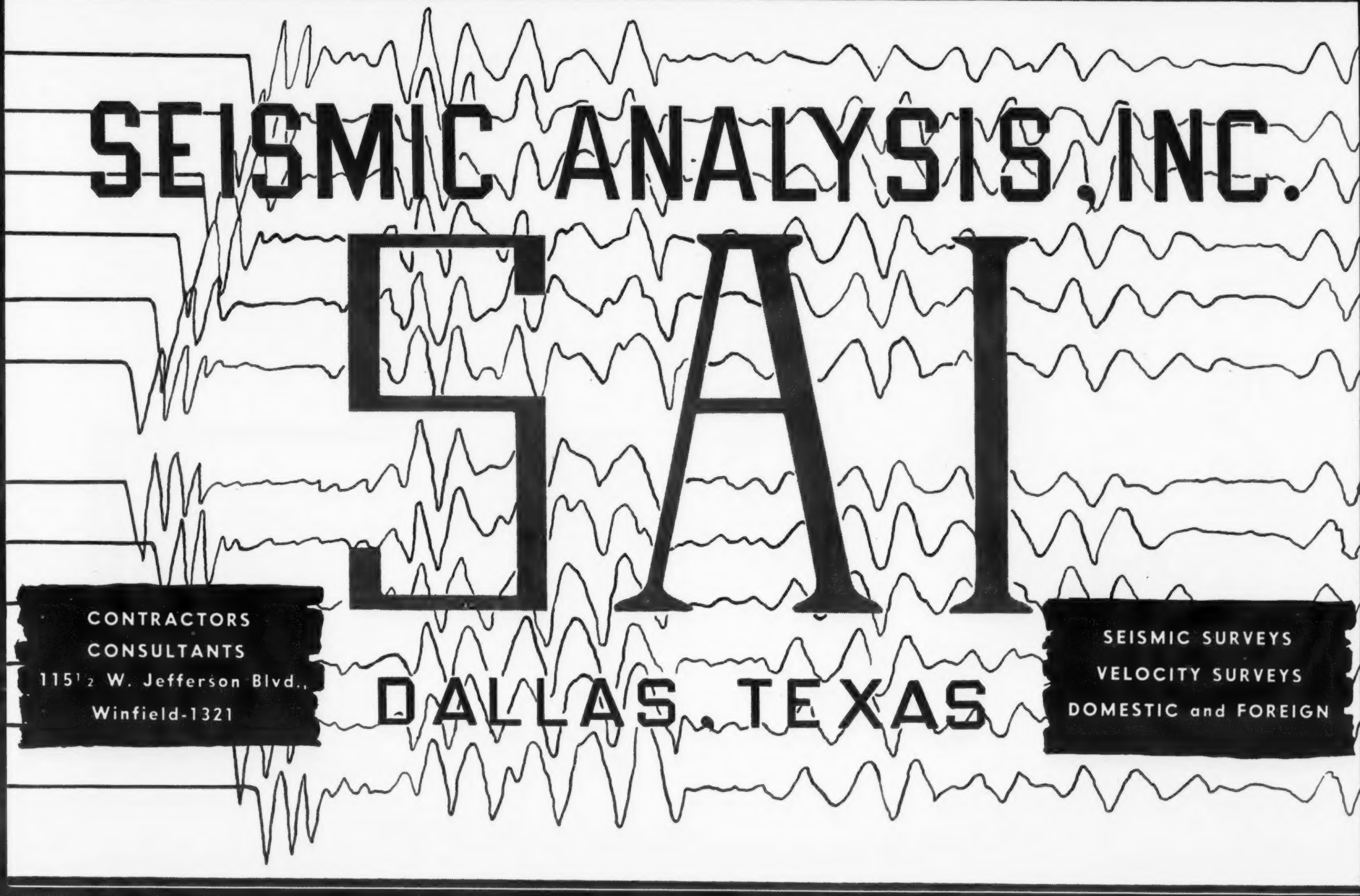
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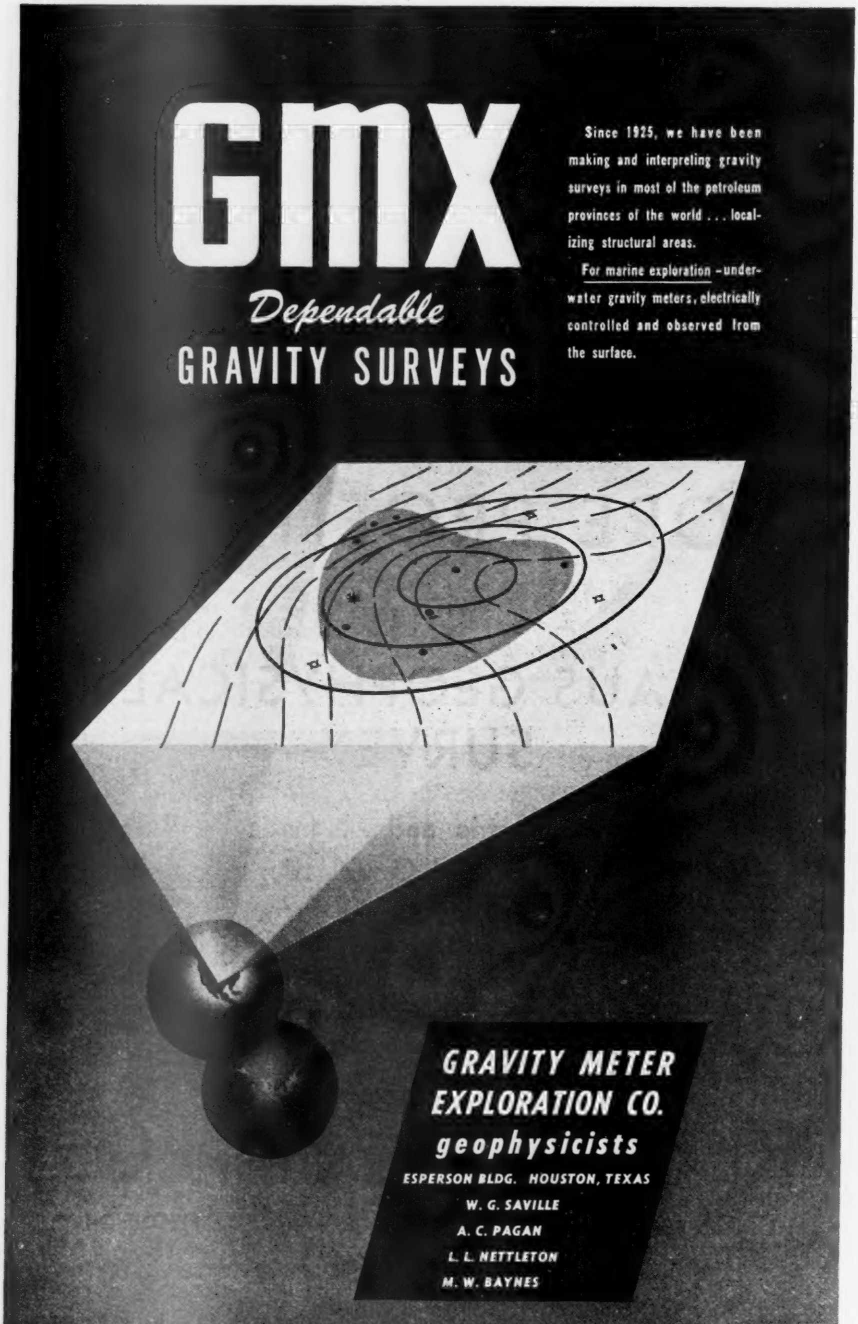
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